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PREFACE

This is the final number of Volume 47 of the Quarterly TRANSACTIONS of the A. I. E. E., comprising the papers and discussions of the New Haven Regional Meeting (May 1928) and the 1928 Summer Convention (Denver, Colorado, June 25-29), as well as the president's address and technical committee reports presented at the latter. Papers from the regional meetings held at Spokane and Atlanta will appear in the January 1929 Quarterly.

"An Amplifier to Adopt the Oscillograph to Low-Current Investigations," Mr. Sigmund K. Waldorf's prize paper, is published here.

This number concludes with the topical and author's index to Volume 47.

Application of Wound Type Current Transformers Installed in High-Voltage Oil Circuit Breaker Tanks

BY J. C. REA[1]

Associate, A. I. E. E.

Synopsis.—*Wound type current transformers installed in the tanks of high-voltage oil circuit breakers have been in operation for many years. The experience gained during this period has resulted in fairly clear definitions as to the types of installations to which they are best suited, and to designs of transformers which are highly reliable. The purpose of this paper is to present a brief history of some of the developments leading up to the present application of wound type current transformers in circuit breakers and to indicate some of the conditions under which they offer special advantages.*

* * * * *

In the early stages of the electric power industry the oil circuit breaker made its appearance as a solution of the problem of interrupting circuits under load and it was not surprising that efforts were soon made to develop automatic mechanisms which would cause the circuit breaker to open itself on over-current. Some of the earliest forms of devices for performing this duty took the form of solenoid coils connected in series with the circuit controlled by the circuit breaker. These coils acted as electromagnets in a mechanism which was designed to release the operating mechanism of a circuit breaker when a predetermined amount of current flowed through the series coil. The operating mechanism would then throw the circuit breaker to the open position.

A device of this nature was manufactured in 1910 for installation on indoor circuit breakers where it was unnecessary to protect it from the weather. The series coil was mounted on the top of the oil circuit breaker bushing and the motion of the electromagnet was transmitted to the control mechanism through a glass tube which served to insulate the electromagnet from the control mechanism. A further step in the development of this device was to provide for its protection from the weather when used in outdoor oil circuit breakers. This was accomplished by moving the series trip coil to the inner end of the entrance bushing where it operated submerged in oil.

The series trip coil was mounted on the lower end of the bushing. An insulating plate was bolted between the lower end of the bushing conductor and the support for the breaker contact. The series trip coil was connected across this insulating member so that the current flowing through the breaker passed through the trip coil.

The motion was transmitted from the electromagnet to the control mechanism by means of a vertical insulating rod which connected to a lever on a shaft running between the three phases of the circuit breaker. This shaft when rotated released the opening mechanism. Devices of this nature all had the serious defect of requiring very delicate adjustments because the amount of energy available was very small. They also lacked a satisfactory means for varying the time delay.

These defects were readily overcome by the use of current transformers connected to suitable relays. The desired time delay characteristics were obtainable with this combination and additional features such as differential protection, reverse power control, etc., could also be obtained. The current transformers, however, in many cases added a very considerable item of expense to the installation, particularly in the higher voltages.

The use of the entrance bushing on the oil circuit breaker offered a means to provide insulation for the primary circuit of the current transformer, eliminating one of the heaviest items of expense in connection with its use. This means was used either by applying a bushing type transformer in which the primary winding was formed by the conductor passing through the bushing, or a transformer with a primary coil wound on the core and mounted in the oil circuit breaker tank.

In the case of the bushing type transformer no change was required in the conducting parts of the oil circuit breaker in order to pass the primary current through the current transformer.

In applying the wound-type current transformer inside the circuit breaker tank it was necessary to insert the primary coil in series with the conducting parts in the breaker.

Early Forms of Transformers

In an early form of transformer of this type the primary coil was provided with a bracket which formed one of the leads and was located at the lower end of the bushing. The transformer was arranged with two equal primary windings which could be connected by means of links into either a series or parallel connection so as to obtain two ratios. The bracket lead was fastened to one of the contact members in the oil circuit breaker and formed a partial support for the transformer. The other end of the primary winding

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Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

was connected to the conductor at the lower end of the entrance bushing. An insulating plate, bolted between the lower end of the bushing conductor and the support for the breaker contact, caused the current to flow through the primary coil.

As this transformer was designed for use with circuit breakers having dimensions already established, it was necessary to make the primary coil as small as possible and to aid in obtaining this result the secondary coil was placed on the leg of the core opposite to that on which the primary coil was located. This construction not only permitted a small primary coil to be used but also enabled the insulation to be split into two sections. The core was given an equal amount of insulation both from the primary and the grounded secondary coil so that the dielectric stress on the insulation at the primary coil was considerably reduced from that which would have existed if all of the insulation had been applied at one point. The secondary coil leads were brought out along a bracket connection which was built into the secondary coil and which aided in supporting the transformer by being fastened to the top cover of the oil circuit breaker. Transformers of this type were applied to oil circuit breakers ranging from 22,000 to 110,000 volts. They were used for tripping purposes and for operating indicating ammeters for which they were very satisfactory.

The principal reason for the use of these transformers rather than bushing type transformers was to take care of the tripping of high-voltage oil circuit breakers where the current at which tripping was desired was so low that satisfactory performance could not be obtained with bushing type transformers. The accuracy of ratio and phase angle of these transformers with wound primary coils was not sufficient to permit their application to metering. The placing of the primary and secondary coils on the opposite sides of the core also caused a high leakage flux which gave the transformers rather poor characteristics on heavy overloads. This interfered with their application to differential protection of transformer banks.

These weaknesses were not easily remedied because of the space limitations which were imposed on the transformer, due to its being mounted in the tank of the oil circuit breaker. The characteristics obtained and the very material saving in cost over externally mounted transformers made this type of equipment of distinct advantage for many installations.

Further development was made possible by increasing the space available inside of the tanks, permitting the physical dimensions of the transformer to be increased. Improved electrical characteristics were obtained by mounting the primary and secondary coils concentrically upon one leg of the core and increasing the number of ampere-turns and cross-section of core. The characteristics thus obtained made the transformer suitable for metering. The mechanical strength of the transformer as a unit, and also of its mounting in the oil circuit breaker, were also greatly improved by this construction.

The insulation between the primary and secondary coils presents a rather unusual problem because of the possibility of the transformer being operated, at times, in oil of reduced dielectric strength. It is also necessary to provide for a possible accumulation of carbon and other deposits which may adhere to the surface of the insulation.

A type of construction for the major insulation, which has proved highly satisfactory, consists of concentric tubes of laminated phenol compound supported on rings of the same material. Shoulders are turned on the tubes and the supporting rings are pressed against them so that the tubes cannot slip along their axis. The free circulation of the oil between the tubes is insured by perforating the supporting rings. This construction provides for a very long leakage path between the primary coil and ground.

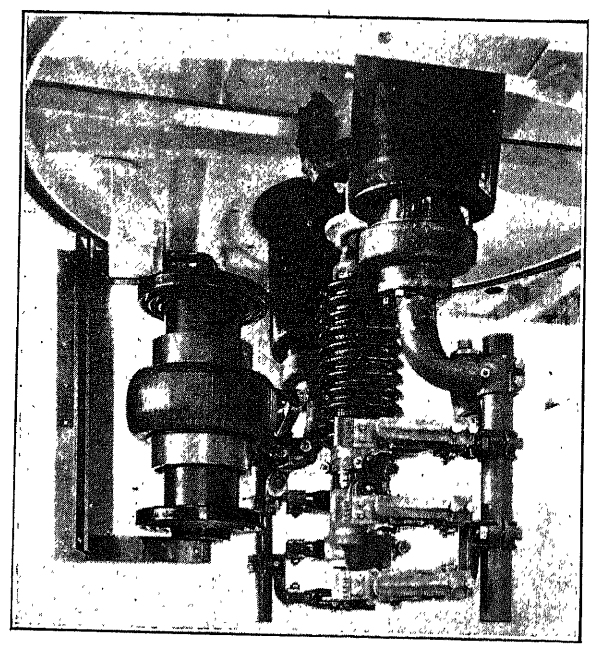

FIG. 1—73-KV. OIL CIRCUIT BREAKERS WITH MODERN WOUND TRANSFORMER

Additional leakage surface is obtained by applying a porcelain tube with a corrugated flange at each end of the Bakelite insulating tube.

MODERN DESIGNS OF TRANSFORMERS

Figs. 1 and 2 show typical transformers of this construction. The outer coil is the primary which in the transformer illustrated is wound in two sections. Links are provided to permit the sections to be connected, either in series or parallel to obtain two different ratios. The secondary coil is wound on a tube which fits against the core, directly under, and concentric with the primary coil. The secondary leads can be seen, running out to the secondary terminal block at the top of the transformer. The symmetrical arrangement

of the coils limits the mechanical forces, due to heavy primary currents, to a minimum.

The mounting of a current transformer in an oil circuit breaker tank calls for particular care because of the mechanical shocks to which the transformer is subjected during the interruption of the circuit by the oil circuit breaker. It has been found that if very substantial support is given to the core of the transformer it will withstand these shocks without sustaining any injury.

Fig. 1 shows a typical mounting of one of these trans-

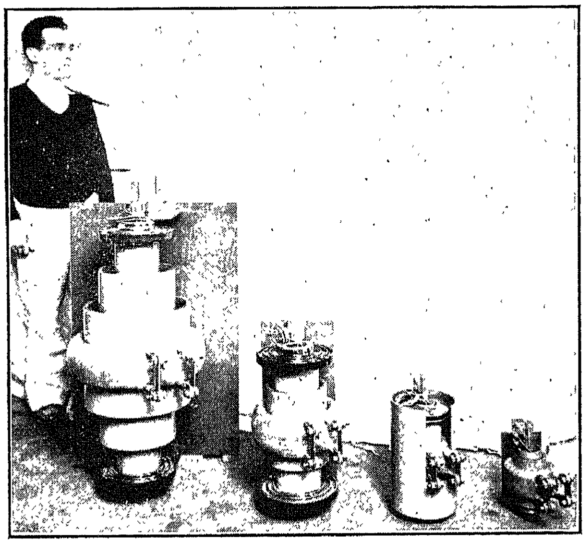

FIG. 2—COMPARISON OF 132-KV., 73-KV., 37-KV., AND 25-KV. TRANSFORMERS

formers in a multiple-break oil circuit breaker of the rotary type. The core is rigidly held by a bracket which is secured to the cover of the oil circuit breaker. The primary coil is in turn fastened to the lower end of the entrance bushing by means of heavy copper links. The location of the transformer relative to the contacts of the breaker is such that it is at no time endangered by proximity to the arcs, which are drawn upon opening the breaker. In extreme cases, where the number of instruments to be operated exceeds the capacity of one transformer, two of these transformers can be mounted in each phase of the oil circuit breaker. In this case one transformer is applied to each of the entrance bushings.

In some of the earlier transformers of this type trouble was experienced due to surges causing a failure of the insulation between turns in the primary coil. Various protective devices were tried. It was found that by applying very generous insulation between turns on the primary all trouble from this source was eliminated and that protective devices to shunt the surges across the primary coil were unnecessary.

A line of transformers has been developed to cover voltages from 25 kv. to 132 kv. The general construction of these transformers is fairly uniform for the entire range of voltages. Fig. 2 shows the relative size of some of these transformers. The smallest transformer shown is rated at 25 kv. The next larger transformer is a special design and is provided with a cylindrical barrier around the primary coil to permit its installation in a 37-kv. circuit breaker which has a very limited space for the transformer. The third transformer is for mounting in a 73-kv. oil circuit breaker, and the largest one is for mounting in a 132-kv. oil circuit breaker.

This type of transformer has been developed to cover the range of ratios from 5/5 up to 400/5. The primary ampere turns on the lower ratio transformers is approximately 1000, while on the higher ratios 1200 ampere-turns are used. This variation in ampere-turns is brought about by the necessity of providing for the additional insulation in the lower ratio primary coils, which have a large number of turns. The characteristics of the transformers are only slightly affected by this variation in the number of ampere-turns for the different ratios.

APPLICATIONS

The application of wound type current transformers in the tanks of oil circuit breakers is particularly advantageous in meeting two distinctly different requirements. One of these cases is where it is necessary to

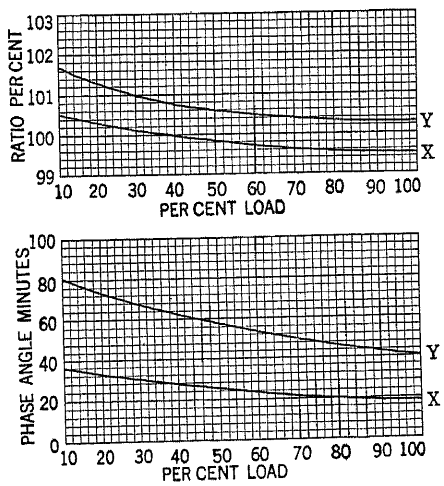

FIG. 3—CHARACTERISTICS OF WOUND TRANSFORMER

X 2.5 Volt-amperes, 90 per cent power-factor burden
Y 15 Volt-amperes, 90 per cent power-factor burden

operate watt-hour meters for measuring small amounts of power, where the required accuracy cannot be obtained from bushing type transformers. The second use to which these transformers can be very advantageously applied is to operate tripping relays where the primary current is low and the secondary burden on the transformer is high.

For the first case, Fig. 3 shows the ratio and phase-angle curves obtained with this type of wound transformers when operating with burdens of 0.1 ohm resistance 0.13 μ h. or approximately 2½ volt-amperes,

90 per cent power factor, and of 0.6 ohms resistance 0.7 μ h. or approximately 15 volt-amperes, 90 per cent power factor. These curves are characteristic for the type of transformers herein illustrated over their total range of 5/5 ratio to the upper limit of 400/5 ratio. Where extreme accuracy is needed the ratios can be adjusted by turn compensation to get zero error at any per cent of primary load desired. This is accomplished by the use of two parallel secondary windings having an unequal number of turns. By choosing a suitable combination of turns for these

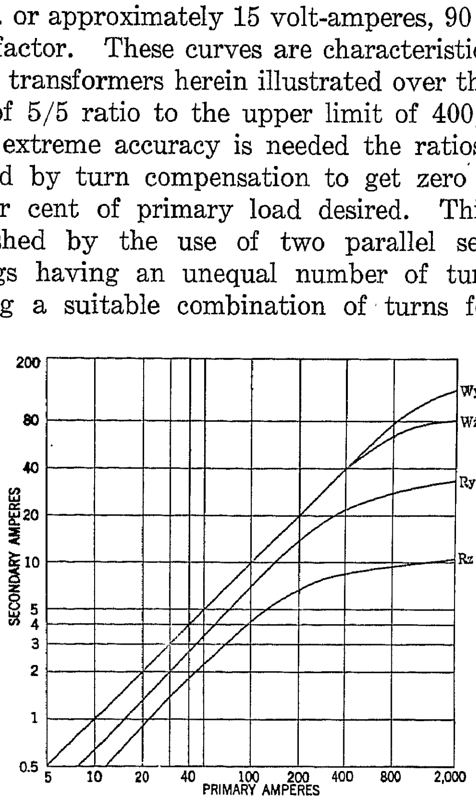

FIG. 4—COMPARISON OF 50.5 RATIO, BUSHING, AND WOUND TYPE TRANSFORMERS

W Y Wound transformer 15 volt-amperes burden
W Z Wound transformer 50 volt-amperes burden
R Y Bushing transformer 15 volt-amperes burden
R Z Bushing transformer 50 volt-amperes burden

secondary coils, the ratio for a given primary current and burden can be adjusted to any desired value.[2]

For the second case, Fig. 4 shows the relation between primary and secondary amperes of a conventional 50/5 ratio (10 secondary turns) bushing type transformer and of a wound type transformer of the same ratio. A rating somewhat below that generally considered the minimum for bushing type transformers was chosen so as to magnify the differences between the two types of transformers.

The effect of the distribution of the primary and secondary windings relative to the core of bushing type transformers has been investigated by the Committee on Protective Devices. (JOURNAL of A. I. E. E., August 1927.) Their report shows that a minor error may be caused by an unsymmetrical distribution of the primary and secondary windings. In order to avoid any error from this cause the curves shown in Fig. 4 were taken from a bushing type transformer in which the secondary turns were evenly distributed around the core, and the primary was carefully centered. The curves are shown for burdens of approximately 15 volt-amperes and 50 volt-amperes.

A point that is occasionally overlooked in the application of induction type over-current relays to current transformers is the excessively high burden which they impose on the transformer when they are connected on the low current taps. A type of relay frequently used with bushing type current transformers has a nominal rating of 2-volt-amperes at the tap current. If such a relay is connected to the transformer and operated on the two ampere tap the impedance of the relay alone is approximately equivalent to a burden of 12.5-volt amperes at 5 amperes secondary current of the transformer.

The usual installation of high-voltage oil circuit breakers, requires a considerable length of wire to be run between the current transformers and the relays. Using No. 10 copper wire for the secondary leads, the volt-ampere burden added by the wire is approximately five volt-amperes for each 100 ft. of distance between the transformer and relay. The curves marked *W Y* and *R Y* in Fig. 4 would be those resulting from the use of a two-volt ampere induction type relay connected on the two ampere tap and mounted 50 ft. from the oil circuit breaker. Using a 50/5 ratio transformer it would be expected that the relay would trip the breaker at a minimum of 20 amperes primary current. However, the chart shows that while this would be true with the wound type transformer it would require a minimum of 30 amperes primary current to operate the relay from the bushing type current transformer. Approximately the same burden would be obtained with a 12-volt-ampere relay connected on the five ampere tap, or a 17-volt-ampere relay connected on the six ampere tap, when either relay is located 50 ft. from the current transformer.

The curves marked *W Z* and *R Z* are those obtained

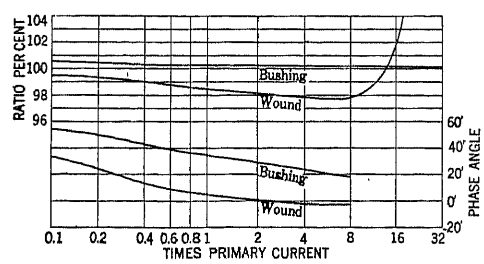

FIG. 5—400 TO 5 RATIO, WOUND, AND BUSHING TRANSFORMERS

Burden 2.5 volt-amperes, 90 per cent power factor

with a secondary burden of 50 volt-amperes, 50 per cent power factor. Approximately this amount of burden would be imposed by a 2-volt-ampere relay connected on the one ampere tap or a 17-volt-ampere relay connected on the 3-ampere tap, either of these being located 50 ft. away from the circuit breaker. In this case the bushing type transformer would require more than twice the primary current to operate the relay than that required by the wound type current transformer.

It will also be seen that the ratio of the bushing type

2. Patent No. 1,550,906.

transformer varies considerably throughout the range of primary currents and that it becomes very bad at from five to eight times normal current, whereas the wound type transformer has a very small error until the primary current rises to around 20 times normal. This characteristic of the wound type transformer makes it particularly suitable for use on differential protection of transformer banks where the characteristics of the current transformers on both sides of the bank must be carefully matched in order to prevent the operation of the relays on heavy through short circuits.

The upper limit of ratios at which it is desirable to apply the wound type current transformer in circuit breaker tanks is fixed by two considerations. The one is a mechanical, and the other an electrical limitation. The duty required of the circuit breaker for rupturing heavy currents usually varies somewhat in proportion to the current which will normally be carried by the breaker. The mechanical strains placed on the transformer are greatly increased where the circuit breaker is used to interrupt very heavy currents.

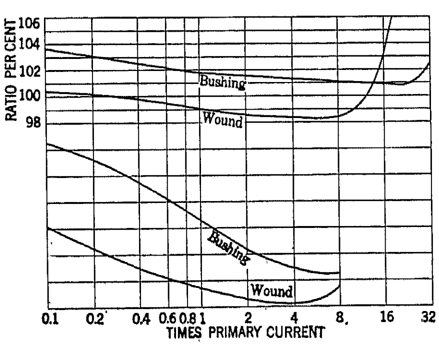

FIG. 6—400 TO 5 RATIO, WOUND, AND BUSHING TRANSFORMERS

Burden, 15 volt-amperes, 90 per cent power factor

This means that even though transformers might be built for heavier primary currents than 400 amperes, their installation in circuit breakers, which are required to carry larger amounts of current, would in many cases be hazardous, because of the severe shocks to which they would be subjected under short circuits and the heavy mechanical forces which would be imposed on them by the explosion when the breaker interrupts the circuit. A second limitation places the 400/5 ratio as a reasonable upper limit for these transformers, because the accuracy of a bushing type transformer of this ratio is approximately as good as that of the wound type transformer.

Figs. 5, 6, and 7 show the comparison between ratio and phase-angle curves of a conventional 400/5 ratio bushing transformer and of the wound type transformer of the same ratio. The curves have been plotted on semi-logarithmic scale so as to condense the portion of the chart beyond full load primary current. The curves in each case were taken without compensating the transformers for the particular burden. This permits direct comparison to be made from one chart to the other to observe the effect of changing the

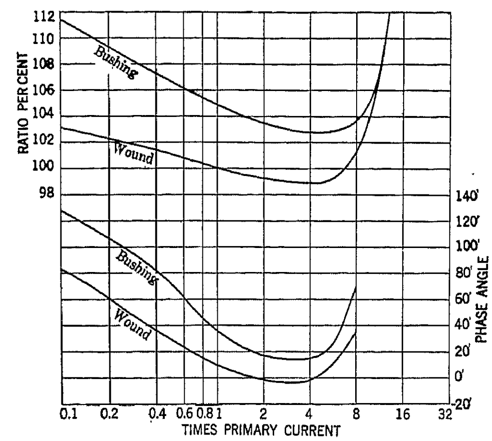

FIG. 7—400 TO 5 RATIO, WOUND, AND BUSHING TRANSFORMERS

Burden, 50 volt-amperes, 50 per cent power factor

secondary burden on either transformer. These curves show that for a very low burden the bushing type transformer has a better ratio but poorer phase angle than the wound transformer, and that if the burden is increased the wound type transformer has much better characteristics than the bushing type.

CONCLUSIONS

1. Experience has shown that wound type transformers can be safely installed in the tanks of high-voltage circuit breakers, in many cases, at a very substantial saving of cost over externally mounted transformers.

2. For heavy secondary burdens these transformers can be built to give characteristics that are much better than those of bushing type transformers where the ratios are less than 400/5.

3. For light burdens the wound type transformers offer a means of obtaining characteristics which are suitable for metering at low ratios where bushing type transformers would be entirely unsatisfactory.

Relation between Transmission Line Insulation and Transformer Insulation

BY W. W. LEWIS[1]
Member, A. I. E. E.

DURING the past few years, the great majority of overhead transmission systems in this country have grounded the neutral either solidly or through a moderate resistance.[2] Overvoltages due to arcing grounds on such systems are practically absent. Overvoltages due to switching are in general no longer feared on systems with modern insulation and apparatus.

Lightning is the only cause of high voltage which gives serious concern at the present time.[3] In order to combat lightning, transmission engineers have been adding more and more insulation to the lines as well as various special arcing devices, overhead ground wires, etc. A great deal of work has been done in studying lightning and its accompanying phenomena by means of the klyodonograph and surge voltage recorder.[4]

Laboratory work has thrown a great deal of light on the effect of impulses on insulation, both of apparatus and transmission lines.[5]

The question now arises as to whether, in the light of present knowledge, we can design a transmission line and its connected apparatus so that they will be reasonably safe against breakdown and interference to service due to lightning. Let us first examine the data upon which such a design shall be based.

Sixty-cycle flashover tests on insulators have been made on strings of various numbers of disks. Most of these tests have been made on standard 10-in. disks, spaced 5¾ in. apart. It has been found that the flashover value when plotted against length of string in inches, gives a straight line on log-log paper. The length of string is the spacing per disk times the number of disks. The curve may also be used for insulators of other spacings not differing greatly in proportions from the 10-in. disk spaced 5¾ in. apart. In this case, it is only necessary to multiply the spacing per disk by the number of disks, and enter the curve with the total distance. Table I gives the length of string and 60 cycle flashover for strings of 10 in. disks spaced 5¾ in. apart. The flashover values are plotted against number of disks on Fig. 1.

The impulse flashover of such insulator strings assumes various values, depending on the nature of the impulse, the steepness of its front, the slope and length of its tail, etc. Numerous tests have been made with the standard wave of the High-Voltage Laboratory at Pittsfield on insulator strings of various lengths, and these tests have been repeated with a great deal of consistency.

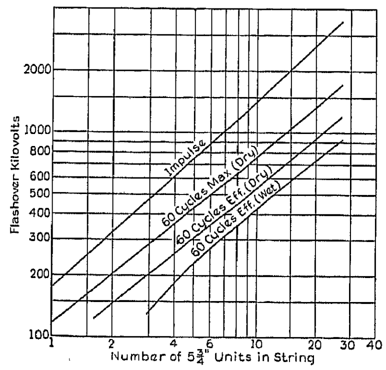

FIG. 1

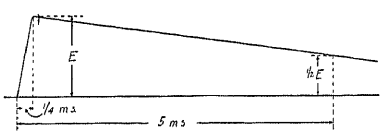

FIG. 2

The Pittsfield wave is a single impulse with a very steep front, rising to its crest value in approximately one-quarter microsecond or less, (depending on the load on the test set), and then decreasing to 50 per cent of the crest value in approximately five microseconds, *i. e.*, the portion of the wave above 50 per cent crest value is approximately one mile in length. This wave is represented in Fig. 2.

The manner of making the tests is to impress on the insulator string such a voltage that the arc-over takes place somewhere on the tail of the wave. The actual

1. Central Station Engineering Dept., General Electric Co., Schenectady, N. Y.

2. *Present Day Practises in Grounding Transmission Systems*, Report of Subcommittee on Grounding of Protective Devices Committee, TRANS. A. I. E. E., Vol. 42., 1923, p. 753.

3. *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines*, Sindeband and Sporn, TRANS, A. I. E. E., Vol. 45, 1926, p. 770.

1926 Lightning Experience on 132-Kv. Transmission Lines, P. Sporn, 1928. A. I. E. E. Quarterly TRANS. No. 2.

Recent Investigation of Transmission Line Operation, J. G. Hemstreet, TRANS. A. I. E. E., Vol. 46, 1927., p. 835.

4. *Klydonograph Surge Investigations*, Cox, McAuley, and Huggins, TRANS, A. I. E. E., Vol. 46, 1927, p. 315.

Measurement of Surge Voltages on Transmission Lines Due to Lightning, Lee and Foust, TRANS, A. I. E. E., Vol. 46, 1927, p. 339.

5. *Lightning and Other Transients on Transmission Lines*, F. W. Peek, TRANS. A. I. E. E., Vol. 43, 1924, p. 1205.

Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

flashover value is determined by adjusting a sphere-gap in multiple with the insulator string until about one-half of the flashovers take place over the insulator string and one-half over the sphere-gap. The setting of the sphere-gap is then taken as a measure of the flashover potential. The values thus determined (Table I), plotted against length of string, again form a straight line on log-log paper somewhat above the 60-cycle values (Fig. 1).

The ratio of the impulse flashover to the 60-cycle

TABLE I
FLASHOVER OF INSULATOR STRINGS BASED ON 10-IN. DISKS SPACED 5¾ INCHES

No. disks	Length of string inches	60-cycle arc-over kv. eff.	Impulse arc-over kv. max.
3	17.25	200	470
4	23.	255	610
5	28.75	305	750
6	34.5	355	890
7	40.25	400	1020
8	46.	445	1150
9	51.75	490	1280
10	57.5	540	1410
11	63.25	580	1520
12	69.	620	1660
13	74.75	660	1780
14	80.5	700	1900
15	86.25	745	2020
16	92.	785	2140
17	97.75	820	2260
18	103.5	865	2380

maximum or crest flashover is called the impulse ratio.[6] It will be seen that this varies from approximately 1.5 to 2 within the range of the curves. A fair average would be 1.8.

If an extremely high potential is applied as compared with the flashover value of the insulators on the tail of the wave, then flashover will take place on the front of the wave. For the particular wave we have been discussing, it has been found that the flashover values thus found are very consistently about 20 per cent greater than the values determined when the flashover takes place on the tail of the wave. For other waves, of course, there may be a somewhat different relation between flashover on the front and tail of the wave.

In actual practise, flashover of insulator strings may take place either on the front of the wave or on the tail of the wave, and sometimes even on the crest of the wave. In case flashover takes place on the front of the wave, then only a small portion of the wave passes on to the rest of the line and station apparatus (Fig. 3A.) When flashover takes place on the tail of the wave, a longer portion of the wave passes on, and as this represents a greater amount of energy, the wave is capable of doing considerable damage if it reaches station apparatus (Fig. 3B). If the value of the wave is not quite sufficient to flash over the insulator string either on the front or the tail, then the full wave will pass on toward the station (Fig. 3C). In each case, there may be considerable attenuation along the line before the wave reaches the station.

Some data have been taken on oil-filled bushings and pedestal type insulators, such as used on disconnecting switches. These data indicate an impulse ratio slightly higher than for line insulators. There appears to be a similar difference of approximately 20 per cent between the flashover value on the tail of the wave and on the front of the wave with the particular wave used in the tests.

During the past few years, numerous data have been accumulated by means of the klydonograph and surge voltage recorder, which has indicated the maximum voltage to be expected on transmission lines with present standards of insulation to be in the neighbor-

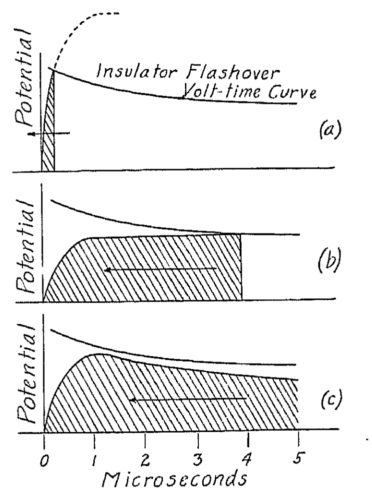

FIG. 3

hood of 10 to 12 times the crest value of the line to neutral voltage of the system.[4]

Table II gives the average number of insulator disks used on actual systems, also the minimum and maxi-

TABLE II
INSULATION OF ACTUAL LINES

System voltage kv.	Crest value line to neut. voltage kv.	No. of insulator disks: Range	No. of insulator disks: Weighted average	Impulse flashover kv.	Ratio impulse to normal voltage
66	54	4–6	5	750	13.9
88	72	5–7	6	890	12.4
110	90	6–9	7	1020	11.3
132	108	9–12	10	1410	13.1
154	126	10–12	10	1410	11.2
187	153	10–12	10	1410	9.2
220	180	12–16	13	1780	9.9

mum number of disks for the various standard system voltages, the data being compiled mainly from the *Electrical World Supplement* of January 3, 1925. The impulse flashover value is given also. From this table it will be noted that the impulse flashover value

6. *Effect of Transient Voltages on Dielectrics*, F. W. Peek, TRANS. A. I. E. E., Vol. 34, 1915, p. 1857.

is in the neighborhood of 10 to 14 times the crest value of the normal line to neutral voltage. This, together with the results of the klydonograph study, would indicate that the impulse flashover values given in Fig. 1 are fair values to use for the type of impulse which causes flashover on actual systems.

According to Mr. F. W. Peek's investigations, we may take the maximum potential gradient which may be induced on a transmission line by lightning as approximately 100 kv. per ft. of height of conductor. Actually, there have been measured by surge-voltage recorder, potentials which indicate gradients as high as 40 kv. per ft. of height. The readings obtained are subject to the fact that there is no assurance that the surge voltage recorders were located at the point of highest potential. The potentials are naturally limited by the insulator flashover, and such flashover potentials would require gradients in some cases as high as 60 kv. per ft. of height.

Assuming that the maximum potential gradient of 100 kv. per ft. of height can be obtained, and assuming further, that the flashover values given in Fig. 1 are substantially correct, then we have a means of determining whether or not a particular line will be subjected to flashover.

Mr. Peek, in his laboratory investigations, has determined fairly well the effectiveness of overhead ground wires. The protection afforded by the overhead ground wire depends on the distance of the ground wire from the conductors, on the height of the conductors above ground, and on the size of the ground wire and conductors. Generally speaking, however, any one of these factors may be varied within the range of practise without affecting the protective ratio to any great extent. The resistance of the connection to ground also has considerable influence on the protection.

Tables III, IV, V, and VI give comparative protective ratios for various average arrangements of practical transmission lines, assuming ground connections of low resistance. These values have been worked out by Messrs. Peek, Lloyd, and Clem and are based on calculation and tests on laboratory models. It is believed that they are fair values to use, although it is difficult to verify them definitely on actual transmission lines, except by a comparison of operating experience with and without ground wires.[3]

The values in Tables III to VI are given with considerable apparent accuracy, merely for the purpose of bringing out the difference between the various arrangements. However, in using values from the tables for calculations, they should be considered quite approximate.

The tables show ratios considerably greater than can be obtained by calculation with the classical formulas. Mr. C. A. Woodrow has offered an explanation of this as follows:

The potential gradient at the surface of the conductors and ground wire under lightning conditions, greatly exceeds the rupturing potential gradient of air. The air breaks down, forming corona, thus in effect enlarging the diameter of the conductors and ground wire. This, in turn, increases the capacitance between conductors and ground wire and correspondingly decreases the induced voltage on the conductors.

In placing ground wires it is desirable to adhere to the following general rules.

TABLE III
EFFECT OF GROUND WIRES ON EXCESS VOLTAGE, CONDUCTORS HORIZONTALLY ARRANGED

Arrangement	Protective ratio		Per cent decrease in excess voltage
. o o o 1 2 3	(1)	0.45	55
	(2)	0.45	55
	(3)	0.52	48
. . o o o	(1)	0.37	63
	(2)	0.32	68
	(3)	0.37	63
. o o o	(1)	0.50	50
	(2)	0.44	56
	(3)	0.50	50
. . . o o o	(1)	0.30	70
	(2)	0.27	73
	(3)	0.30	70
. . o o o .	(1)	0.32	68
	(2)	0.28	72
	(3)	0.32	68
. o o o . .	(1)	0.34	66
	(2)	0.31	69
	(3)	0.34	66

o Indicates conductor
. Indicates ground wire

$$\text{Protective Ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

TABLE IV
EFFECT OF GROUND WIRES ON EXCESS VOLTAGE CONDUCTORS VERTICALLY ARRANGED

Arrangement	Protective ratio		Per cent decrease in excess voltage
. o o o o o o	(1)	0.42	58
	(2)	0.52	48
	(3)	0.62	38
. . o o o o o o	(1)	0.33	67
	(2)	0.39	61
	(3)	0.48	52
. o o o o o o .	(1)	0.40	60
	(2)	0.45	55
	(3)	0.42	58
. o o o . . o o o	(1)	0.46	64
	(2)	0.38	62
	(3)	0.44	56
. . . . o o o o o o	(1)	0.28	72
	(2)	0.33	67
	(3)	0.41	59

o Indicates conductor
. Indicates ground wire

$$\text{Protective ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

TABLE V
EFFECT OF GROUND WIRES ON EXCESS VOLTAGE CONDUCTORS HORIZONTALLY ARRANGED

Arrangement	Protective ratio		Per cent decrease in excess voltage
. .			
o o o o o o	(1)	0.50	50
1 2 3 4 5 6	(2)	0.42	58
	(3)	0.36	64
. .	(1)	0.43	57
o o o o o o	(2)	0.41	59
	(3)	0.42	58
. . .	(1)	0.39	61
o o o o o o	(2)	0.35	65
	(3)	0.28	72
. . . .	(1)	0.33	67
o o o o o o	(2)	0.28	72
	(3)	0.26	74
. . . . .	(1)	0.31	69
o o o o o o	(2)	0.26	74
	(3)	0.23	77

o Indicates conductors
. Indicates ground wire
Conductors 6, 5, 4 have same protective ratio as 1, 2, 3 respectively

$$\text{Protective Ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

TABLE VI
EFFECT OF GROUND WIRE ON EXCESS VOLTAGE CONDUCTORS TRIANGULARLY ARRANGED

Arrangement	Protective ratio		Per cent decrease in excess voltage
.			
o 2 o5			
	(1)	0.53	47
o o o o	(2)	0.47	53
1 3 4 6	(3)	0.51	49
.			
o . o	(1)	0.42	58
	(2)	0.36	64
o o o o	(3)	0.38	62
.			
o o	(1)	0.45	55
	(2)	0.42	58
o o o o	(3)	0.42	58
.			
.			
o o	(1)	0.31	69
	(2)	0.32	68
. o o o o .	(3)	0.30	70

o Indicates conductors
. Indicates ground wire
Conductors 6, 5, 4 have same protective ratio as 1, 2, 3 respectively

$$\text{Protective Ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

1. The wires should be connected to each tower or connected to ground at each wooden pole.
2. The resistance of the tower footing or the pole ground must be low in order to give the maximum protection.
3. The ground wire should preferably be of the same material as the conductor, or other high conductivity material. This will prevent rusting and will have an appreciable effect in reducing the impedance of the system to line-to-ground short circuits. It will also reduce telephone interference by shunting a good portion of the short-circuit current away from the ground.
4. The ground wires should terminate at the station structure rather than at the first or second tower out on the line. This assures that the last span or two near the station, will be protected, and that there will be no abrupt change in the surge impedance of the line at the terminal of the ground wire. Such a change in surge impedance tends to cause an upward reflection in the voltage of a wave arriving on the transmission line.

The conductivity of the ground wire apparently has very little effect on its protective value, as the protective value depends on the reduction in charge on the line conductors and the increase in capacitance of the conductors to ground, and this is independent of the material of the ground wire. High conductivity is very beneficial, however, in relaying and in preventing telephone interference as previously mentioned.

Now, if we know the potential gradients which may be due to lightning, the flashover value of the line insulators and the protection afforded by overhead ground wires, we are in a good position to determine what must be done to render the transmission line fairly safe from insulator flashover.

In Table VII are given the actual average heights of the lowest conductor at the tower for the various standard system voltages as disclosed mainly from a study of the data given in the *Electrical World Supplement* of January 3, 1925. In this table are given also the potentials which may be obtained with a gradient of 100 kv. per ft. Comparing these potentials with the flashover value of the line insulators in Table II, we see that it is possible to have insulator flashover under the assumed conditions for every system voltage.

TABLE VII
HEIGHT OF ACTUAL LINES AND INSULATION REQUIRED TO PREVENT FLASHOVER

System voltage	Average height of lowest conductor at tower feet	Possible lightning potential 100 kv. per ft.	Potential with two ground wires conductors horizontally arranged	No. of ins. disks required to prevent flashover	Flashover of insulator disks kv.
66	35	3500	1290	9	1280
88	39	3900	1440	10	1410
110	47	4700	1740	13	1780
132	47	4700	1740	13	1780
154	50	5000	1850	14	1900
187	50	5000	1850	14	1900
220	56	5600	2070	16	2140

Assuming the average heights shown in Table VII and a horizontal arrangement of conductors with two overhead ground wires placed above and between the conductors, the potential induced on the conductors will be reduced to approximately 37 per cent of the value without ground wires; *i. e.*, to the values shown in the fourth column of Table VII. Now, in order to prevent flashover, it will be necessary to use the number of insulator disks shown in the fifth column of the table. The insulation required to produce immunity in this

manner is considerably higher than the present standard.

Of course, if the conductors were arranged vertically, the situation would be still less favorable. For example, let us assume the heights for top, middle, and bottom conductor shown in Table VIII. Then the potentials without ground wire at 100 kv. per ft. of height would be as given in the third column of the table. Now assume that there are two ground wires placed vertically above the two circuits of a double circuit arrangement. Using the protective ratio given in Table IV, we should arrive at the potentials given in the fourth column of Table VIII. In order to prevent flashover in this case, it would be necessary to use the number of insulator disks shown in the fifth column of this table.

Mr. Peek has found that grading rings, properly proportioned and properly located, will increase the flashover value of a string of insulators, (especially strings containing 10 disks and over), approximately 10

TABLE VIII
VERTICAL ARRANGEMENT OF CONDUCTORS, POTENTIAL INDUCED, AND INSULATION NECESSARY TO PREVENT FLASHOVER

Conductor	Conductor Height ft.	Potential without ground wires 100 kv. per ft.	Potential with two ground wires 100 kv. per ft.	No. of insulator disks required to prevent flashover	Impulse flashover kv.
Top.......	75	7500	2480	19	2500
Middle....	60	6000	2340	18	2380
Bottom....	45	4500	2160	16	2140

to 15 per cent and this effect may be taken advantage of in reducing the number of insulator disks or in increased factor of safety.

It is apparent from this study that the potential induced on a transmission line is independent of the operating voltage, except in so far as the height of the conductors and the number of insulator disks is affected by the operating voltage. In selecting the number of insulator disks, it may not be necessary to consider the extreme potential gradient of 100 kv. per ft. of height. A gradient of 75 kv. per ft. will probably be sufficient to cover the great majority of cases, and a line insulated for this gradient would no doubt be immune from flashover except in rare instances.

Now, what is the situation as regards apparatus insulation, especially transformer insulation. The insulation of power transformers is designed to withstand a certain 60 cycle high potential test, this high potential test being, for fully insulated transformers, two times the line-to-line voltage. The test is applied from high tension winding to low tension winding and ground. In the so-called reduced insulation transformers, which are built for operation with solidly and permanently grounded neutral, an induced voltage test of 2.73 times the leg voltage is given to the transformer windings.

Naturally the designers build into the transformer a factor of safety over the Institute test. Such a factor of safety has been worked out by experience and has proved ample to meet the various switching and arcing ground surges to which transformers are subjected.

With the range of line insulation shown in Table II it has been possible for transformers to be subjected to lightning voltages from 10 to 14 times the normal operating voltage with the average line insulation and more than that with the maximum insulation shown in the table. Such voltages, of course, are subjected to the modification caused by lightning arresters, the capacitance to ground of steel work used in supporting bus structures, etc. Also on any system probably only a fraction of the lightning discharges takes place near stations. However, it is reasonable to suppose that transformers have been subjected many times to ten times normal voltage. Transformers have operated under these conditions with remarkable success, the failures due to all causes including lightning, being only a fraction of one per cent per year.

It is reasonable to conclude that fully insulated transformers with present standards of insulation will operate successfully on systems with present average insulation. If such line insulation is increased, as now seems to be the tendency, then the transformer insulation must be correspondingly increased, unless the present standard line insulation is retained for a reasonable distance adjacent to the station, say, one-half to one mile.

If fully insulated transformers are on a par or slightly stronger than the present average line insulation, then it is apparent that reduced insulation transformers are too weak, as their strength is only about 80 per cent of that of fully insulated transformers. Reduced insulation transformers for this reason have no place on systems subjected to much lightning, unless the adjacent line insulation is correspondingly reduced.

In order to protect transformers now in operation and future transformers with standard insulation, it is recommended that the line insulation adjacent to stations be not increased beyond the values given in Table IX for at least one-half mile from the station.

TABLE IX
RECOMMENDED LINE INSULATION

System voltage kv.	Recommended 60-cycle arc-over of line insulators–kv. effective	Corresponding number of 10-in. disks spaced 5¾ inches
66	255	4
88	355	6
110	400	7
132	445	8
154	540	10
187	620	12
220	700	14

Beyond that point there is no objection to increasing the line insulation to any value required to give good operation. Such a practise on the part of the operating

companies will give the manufacturers a definite standard with which to compare their apparatus design.

If for any reason it is desired to increase the line insulation adjacent to the station, then the apparatus insulation should be increased correspondingly.

In cases where it is thought desirable to increase the line insulation and it is feared that maintaining normal insulation near the station will increase the number of flashovers, this may be compensated for by placing additional ground wires over this portion of the line, thereby reducing the potential induced by adjacent cloud discharges to correspond to the reduced number of insulator disks. Such ground wires should extend to the stations and, in some cases, over the stations, in order to insure that the station apparatus secure the full benefit of the ground wires.

The impulse flashover value of standard General Electric bushings is, in general, on a par with the line insulation strength. If a wave gets by the line insulation without flashing over, and reflects to a higher magnitude on reaching the transformer winding, the bushing may flash over and thus offer a means of relieving the transformer insulation. The character and type of waves are so varied that neither the line insulation nor the bushing may be depended upon to protect the transformer in all cases. All that can be said is that if their flashover value is not too high with respect to the transformer strength, there is a pretty good chance that they will flash over and relieve the transformer of at least the greater part of the energy of the wave.

Sometimes power companies call for an especially tall bushing, where the transformer is operated in a district subject to smoke, dust, salt spray, etc. These foreign materials together with moisture reduce the flashover voltage of the bushing. In these cases the long bushing may be used to improve the creepage situation, and the impulse flashover may be kept down to correspond with the transformer insulation by a suitable auxiliary ring or horn gap. Such increased length bushings may afford only temporary relief from creepage as in time dirt will accumulate and their flashover voltage may be reduced to a value comparable to that of a standard bushing. Frequent cleaning may be necessary in either case.

In order to provide a further assurance of successful operation and take care of surges of all kinds, it is necessary to by-pass the incoming surge. The cheapest and most effective present form of such a by-pass, is a lightning arrester.

Mr. K. B. McEachron found that by means of the cathode ray oscillograph, lightning arresters of the oxide film type will hold down the voltage to approximately 1 to 1.8 kv. per cell, depending on the steepness of the wave front.[7] The value of 1.8 kv. per cell corresponds to the standard Pittsfield wave which we have been discussing, and probably also to the steepest waves likely to be encountered in service. Such an arrester, if placed directly at the transformer terminals or as near to the transformer terminals as physically possible, will prevent appreciable reflection and hold down the voltage to a value that is safe under all conditions.

In selecting arresters, the number of cells for a given system is varied, depending on the dynamic overvoltage which may be expected when the load is dropped, in which case the over-speeding of the prime mover and the regulation of the generator may cause a considerable rise in voltage. If this dynamic voltage can be kept to a low value by distribution of load and relaying of the system, or if it naturally comes to a low value owing to the characteristics of generator and prime mover, then a fewer number of cells may be used and still better protection may be secured. This is a very important point and one that should be taken into consideration in all cases.

To summarize: We have shown that it is possible to increase the safety of transmission lines and apparatus from lightning disturbances by adhering to the following principles:

a. Construct the transmission line so that the conductors are as near to the ground as the necessary clearances will permit, and preferably build the line with the conductors horizontally arranged.

b. Install one or two overhead ground wires in accordance with the design of the tower and the requirements for reduction in potential imposed by the height of the conductors.

c. Use sufficient insulation on the line to prevent flashover with the maximum potential gradient that may be obtained with the number of ground wires used.

d. Maintain recommended insulation (Table IX) for one-half a mile or so from the station in order to protect station apparatus. Over this section, additional ground wires extending to the station may be used in order to place this section on a par with the over insulated section as far as flashovers are concerned.

e. Install lightning arresters immediately adjacent to the transformers so as to prevent reflection and hold down the potential to a comparativly low value.

Discussion

For discussion of this paper see page 1009.

7. "Protection of Station Equipment on High-Voltage Transmission Lines," K. B. McEachron, *G. E. Review*, May 1928.

Rationalization of Transmission System Insulation Strength

BY PHILIP SPORN*

Member, A. I. E. E.

***Synopsis.**—Experience on high-voltage transmission lines has shown numerous failures of apparatus which have indicated a decided lack of coordination of the insulation strengths of the various parts of the transmission system. Apparatus offered by manufacturers for a given service shows wide variations in insulation values. Again the flashover and the breakdown values are not at present sufficiently standardized to be comparable among manufacturers of the same piece of apparatus. The standard tests on different types of apparatus are not properly correlated.*

This paper, besides discussing the above situation, points out the causes for the present status, and indicates the benefits to be derived by grading the insulation on the entire system. Predetermining the point of electrical breakdown on the system in the case of high voltage surges leads most logically to grading the insulation. This grading should result in fewer major service interruptions, with a localization of trouble on a link of the system where repairs can be made easily and inexpensively.

The paper points out that additional information is required on surge voltage breakdown of insulation to solve the problem completely but shows that with the present information available a start in grading can be made. The different links in the transmission chain are tabulated according to their relative importance and with this as a starting point, the entire grading scheme is developed to the point of showing relative 60 cycle insulation strength required of the different apparatus used on a transmission system.

It is shown: 1, that transmission systems in general, at the present time, are designed without proper consideration from the standpoint of surge voltages which may be imposed upon them; 2, that the grading scheme proposed is possible, although requiring additional operating data and data from the manufacturers to be fully effective; 3, that grading should result in less costly designs and installations; 4, that the net effect will be better performance of the transmission system in service.

* * * * *

I. Introduction

THE idea that it ought to be possible to place insulation strength of the various portions of a transmission system on a rational basis, instead of the present more or less haphazard basis, is perhaps not new, and has undoubtedly occurred to many. It has not occurred to a large enough group, however, or not with potency enough to bring about any action. To the writer the idea first occurred three or four years ago, because the problem was forcefully called to his attention by operating experience. In one particular case, a 23,000-volt belt was placed around a city. The line was well over-insulated; in fact, it was equipped with 45,000-volt pin insulators of an especially liberal design. The following year oil circuit breakers were placed on the loop for sectionalizing purposes. In the first summer of their operation an epidemic of broken bushings on oil circuit breakers, current, and potential transformers broke out. This led to an investigation of the relative insulation values and strengths of the line insulators and of the bushings of the oil circuit breakers and of the current and potential transformers.

In another instance, with a system voltage of 23,000 volts, standard 37,000-volt oil circuit breakers were employed, but the potential transformers and the high voltage metering equipment used on the system was standard 25,000-volt equipment. Here it was found that the trouble was concentrated on the metering equipment and potential transformers, whereas the oil circuit breaker bushings were comparatively free from trouble. On still another system, the transformers employed were not standard transformers but were transformers designed and tested for three times normal line potential instead of the standard double line potential. The insulators, however, employed for insulating the bus and the disconnecting switches, were standard pin type insulators of the approximate rating of the line. Here practically no trouble was experienced with the transformers or their bushings, but a considerable amount of trouble was experienced with the bus insulators due to flashover and breakdown.

All this experience naturally led to the idea that the probable cause of trouble was that a certain part of the system was insulated without regard to the insulation strength of the component parts of the system, and that it was quite possible that the particular part which was heavily insulated was not the right one. This suggested that it ought to be possible to place the entire problem of insulating the various parts of a transmission system on some rational basis, strengthening or weakening either one part or another in accordance with a preconceived and planned system of grading.

Experience gathered since then has shown the desirability of working out some such idea A great deal of this experience has been on a 132,000-volt system. All of it, however, tended to show definitely that some such plan ought to be evolved and that a considerable saving in labor of design and a considerable improvement in the quality of service of the transmission system could be secured if such an arrangement were adopted.

The present paper is to be regarded not as a complete solution but rather an attempt at the beginning of this problem.

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Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

II. Present Status in Regard to Transmission Insulation

Perhaps no better illustration of the present chaotic condition with regard to insulation strength and ratings can be obtained than by an excursion to catalogs of the various manufacturers. Consider the status among the insulator and bushing manufacturers. In Tables I, II, and III are shown the flashover values of 132-kv., 70-kv., and 45-kv. post type insulators of various manufacturers. The flashovers are in many cases

TABLE I
132-KV. POST TYPE INSULATORS

Manufacturers	A	B	C	D	E
Rating (kv.)	*	165	200	140	132
Dry F. O. (kv.)	355	390	398	448	390
Wet F. O. (kv.)	285	315	320	370	287
Shells per unit	3	3	4	1	1
Units per post	3	3	3	8	8
Diameter (in.)	17	17	17	14	11-1/8

*Manufacturer does not rate

TABLE II
70-KV. POST TYPE INSULATORS

Manufacturers	A	B	C	D	E	F	G	H	I
Rating (kv.)	70	70	72	66	73	73	66	70	70
Dry F. O. (kv.)	180	192	215	240	200	195	215	215	218
Wet F. O. (kv.)	..	137	145	148	150	145	135	150	150
Leakage dist. (in.)	38½	39	37½	..	50½	50½	35	40½	..
Shells per unit	..	4	4	..	..	..	3	4	4
Units per post	1	1	1	4	1	1	1	1	1
Diameter (in.)	15	14	15	11–1/8	16	16	13½	14	16

TABLE III
45-KV. POST TYPE INSULATORS

Manufacturers	A	B	C	D	E	F	G	H	I	J	K
Rating (kv.)	45	45	45	45	45	50	44	40	50	45	45
Dry F. O. (kv.)	170	..	143	140	130	135	198	145	190	131	140
Wet F. O. (kv.)	95	..	95	90	95	100	115	110	121	81	..
Leakage dist. (in.)	21¼	25	17½	18½	22½	25	..	..	..	..	25
Shells per unit	2	3	3	2	3	3	1	2	3	3	3
Units per post	1	1	1	1	1	1	3	1	1	1	1
Diameter (in.)	10½	11	10¼	11	9½	10½	11–1/8	12	13½	..	10½

given in the catalog. In other cases they could be obtained only as a sort of special favor. From a surface inspection it will be seen that variations in flashover of from 25 per cent up to 33 per cent are not at all unusual. Yet not all is seen on the surface. Some of the values listed are sphere-gap determinations, others are needle-gap determinations, and still others are given as test values and not as flashover values at all. The manufacturer did not hesitate to give the apparatus a voltage rating; acting on the assumption, presumably, that he was perfectly competent to perform such a function, and that it was not at all necessary for the user of the apparatus to know the basis on which the rating was arrived at. That this indicates a looseness in arriving at ratings is apparent.

No better condition exists in the bushing situation, and Table IV shows that up fully. For example, between manufacturer A and manufacturer C on 132-kv.

TABLE IV
HIGH-VOLTAGE PORCELAIN BUSHINGS

Manufacturer dry or wet voltage rating	A		B		C		D	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
33-kv.	120	95	155	120	140	112	115	70
44-kv.	160	130	180	150	180	145	140	115
66-kv.	190	150	240	200	215	180	170	135
132-kv.	300	200	375	280	385	330	..	..

bushings there is more than a 56 per cent difference in wet flashover value, when expressed in terms of the lower of the two values. Obviously there has been no scientific yardstick employed in the determination of ratings of their bushings by the various manufacturers, or else there would not be the discrepancy and variation shown. Tables like this could be compiled to show similar and worse conditions among other groups of insulators; but it is believed that more than enough has been shown to indicate the general fact that the present system of ratings is confusing, chaotic, and, in fact, very often dangerous.

The situation among the apparatus manufacturers may not be quite so bad, but certainly it cannot be called good or orderly. At the present time we have a group of more or less standard voltages on which the design classes are based; but the various groupings of classes are not the same for different classes of apparatus. Further, among these various groupings there are undoubtedly manufacturing classes and these classes may, and probably do, differ from the usage voltage standards. Again, various parts of specific designs are often not correlated and under many existing conditions, cannot be. For example, there are many switch manufacturers who do not make their bushings; there are many transformer manufacturers who do not make them. It is quite obvious that as long as the bushing manufacturer himself is held to no standards in the rating of his bushings, some of that same confusion is bound to creep into the equipment of which these bushings form a part. This, of course, is not meant to imply that such a situation cannot occur and has not occurred, where all the various parts of a piece of apparatus have been made by a single manufacturer. A number of examples came to hand recently in a test of some distribution transformers, on equipment that has been built now for 30 or 40 years, and for such a standard voltage as 2300 volts, it was found in some cases there was 50 per cent variation in the impulse flashover value of the bushings of transformers of various manufacturers. Obviously one cannot conclude from such experience or data that there was ever very much knowledge on the part of some of the designers with regard to the impulse flashover value of the bushing, or that an attempt had ever been made to correlate any such knowledge.

Nor is there any better agreement among the various state regulatory bodies who formulate state rules and regulations, nor between them and the Safety Code.

Each one of these has attempted to lay down a set of minimum standards but there certainly is no unanimity of opinion or of rule as to what such a minimum should be. A glance at Curves 7 and 8 of Fig. 1 will fully bring this out.

One would think that the operating companies, and those designing and constructing for them, would at least have seen the necessity for bringing some order into this whole problem, but it does not happen to be the case. The more one talks with the manufacturers, the more one realizes the predicament in which they find themselves, in attempting to carry out the various ideas of the various organizations with regard to the relative values of insulations of component parts of apparatus. If one examines different practises one finds one system particularly bent on over-insulating its lines, another system practising over-insulating its transformers and having its bushings of normal strength, and still another following reverse practise of having extra heavy bushings and normal insulation on windings. These conditions will be found to exist in the moderate voltages; and in the higher voltages they are sometimes even worse.

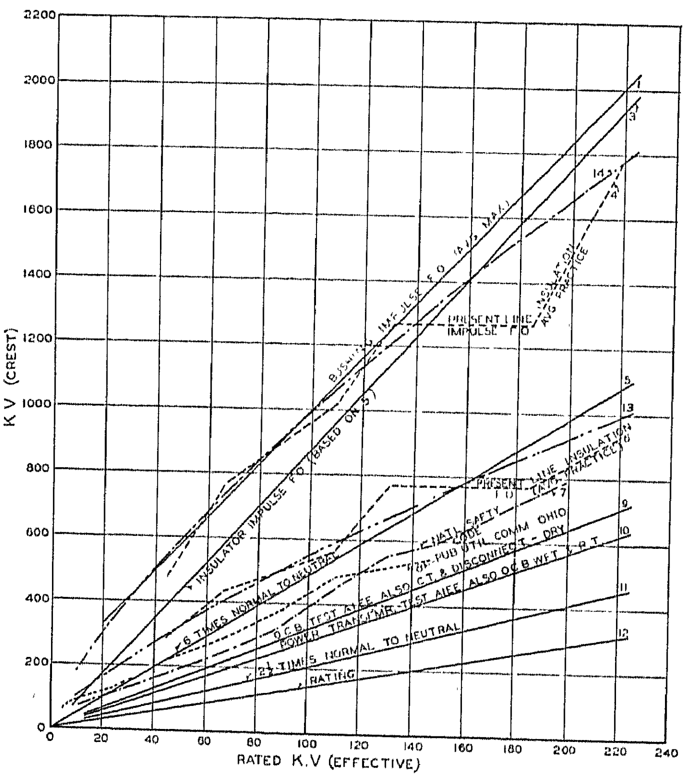

FIG. 1—TRANSMISSION SYSTEM INSULATION STRENGTHS CONDITIONS IN 1927-1928

1 Bushing impulse voltage F. O. (general average)
3 Line insulator impulse F. O. (based on 6 × normal 60 ∼ F. O.)
4 Line insulator impulse F. O. (based on present avg. insulation)
5 6 times normal—line to neutral 60 ∼ voltage
6 Line insulator 60 ∼ F. O. (present avg. insulation)
7 Min. allowable line insulator 60 ∼ F. O.—National Safety Code
8 Min. allowable line insulator 60 ∼ F. O.—Public Utility Comm. of Ohio
9 60 ∼ dielectric test—Oil C. Bs.—C. Ts disconnects—A. I. E. E. dry
10 60 ∼ dielectric test power transfs.—P. Ts dry—O. C B. wet—A.I.E.E.
11 2½ times normal line to neutral—60 ∼
12 Apparatus rating—60 ∼
13 Line insulation (approx. present avg.—60 ∼ F. O.)
14 Line insulation (approx. present avg. impulse F. O.)

The effect of this entire situation is to leave one with a general impression that the whole matter is so confused that it would be hopeless to try to change it and bring order into it. In fact, the suggestion has been made at times that in view of the fact that things are working so well on the whole, it is questionable whether a change ought to be attempted; but with this view the writer finds it very difficult to agree. A glance at Fig. 1 makes it all the more difficult.

In Fig. 1, Curve 12 indicates the crest value of various voltage ratings. Curve 11 shows, for various ratings, the crest value of 2½ times normal from line to neutral. This is the maximum value of potential due to an arcing ground on a grounded neutral system where the system is grounded through a resistor below the critical value.[1] In Curve 10 are shown the standard A. I. E. E. test on power transformers, the wet test on oil circuit breakers, and also the dry test on potential transformers. Curve 9 shows the dry A. I. E. E. test on oil circuit breakers and also test on current transformers and disconnects. Curves 8 and 7 show the minimum insulation strengths required by the Public Utility Commission of Ohio, Administrative Order No. 72, and by the National Safety Code respectively. Curve 6 shows the average practise at the present time on line insulation values.[2] The irregularities in practise disclosed by this curve are unusually interesting. Curve 5 is a line drawn through points representing six times the normal to neutral potential. It has been shown[1] that the maximum potential possible due to an arcing ground on an ungrounded neutral system is approximately six times normal to neutral and Curve 5 is introduced here to show the relationship between it and the curve of present practise.

Curve 4 is a translation of curve 6 in terms of impulse flashover utilizing an impulse ratio of 1.8. Curve 3 is curve No. 5 translated in terms of impulse voltage utilizing the same impulse ratio of 1.8; and curve 1 shows the impulse flashover of bushings for various operating voltages. The impulse breakdown of transformers is not given in curve form as the data on this subject are at present far from complete, particularly on transformers that are now in service and that were designed before the importance that is now being attached to the characteristics, as regards impulse strengths, was given much weight. It is known definitely, however, that there are many cases where impulse breakdown voltage is below bushing flashover value; that is, many cases are known where transformers have failed internally without having any flashovers across their bushings. In other words, the bushings failed to give them the protection that they would be

1. See "Arcing Grounds" by G. E. Clem, *General Electric Review*, Vol. 31—also "Gounding the Neutral through Resistance" by W. W. Lewis, *General Electric Review*, Vol. 31.

2. *Electrical World*, Supplement, January 3, 1925.

expected to give if their flashovers were below the failure point of the transformer itself. It is hard to study the various curves and not come to the conclusion that there is a better arrangement than exists at the present time.

III. Analysis of the Present Situation

An analysis of just how the present situation came about may be of benefit. The present status is the result of a large number of factors. In the first place the art and the industry have grown tremendously, and at a rate that hardly left time for detailed analysis. This is particularly true with regard to the transmission problem. In this country until 10 or 12 years ago, with the exception of a few isolated cases, the transmission problem was one of no great consequence to the average power company. Most of the territories relied on locally placed plants for their important loads; and what transmission was done was for comparatively unimportant load. Further, the amount of capacity involved and general spread of the system were so small that many of the problems with which we are confronted today were not known, or at least existed only in a much milder form. The development during the past decade of networks with large concentrations of power has taken place under pressure of time. Consequently, it is not at all surprising to find ideas that were developed in one territory were taken over, very often bodily, and applied without proper evaluation, in another territory where an entirely different set of conditions existed, and where the same practise could not be followed with impunity. That undoubtedly has been one cause.

Another cause has been the lack of knowledge with regard to the fundamental phenomena that are causing trouble. The present ideas with regard to lightning and surge phenomena had been known for some time but it had never been possible, except with great difficulty, to secure actual data. Lack of facilities both in money and men to carry out any investigations, except by the isolated few, has resulted in a condition where only the most meager data were available on insulation values of insulators and structures, on the causes of flashover, and on the values to be employed in insulation. There has not yet been published or disclosed, at least in this country, an oscillogram of an actual lightning wave. With lack of actual data, therefore, to prove definitely the nature of lightning and of surges, ample room has been left for theorization, and so a number of theories has arisen and flourished, and many installations and designs have been made on the basis of these with, very often, sad results under operating conditions.

Again, as already stated, some of the old high-voltage systems were isolated neutral systems and the insulation values developed for them were based on isolated system operation. Today practically all of the systems are operated with grounded neutral yet no differentiation has been made in the insulation strengths of the two systems. Perhaps none should be made above a certain voltage, if the line insulation is to be chosen primarily with a view of its lightning flashover, but the point is, that if the line is to be designed from a lightning standpoint, that is, if lightning is to be the predominating factor that will determine the line insulation, that ought to be definitely established and the problem will be so much simpler.

Another phase of the lack of knowledge of the fundamental phenomena causing trouble has been the almost complete absence of data on lightning and switching surges and the trouble that they cause. This has been partially remedied in the last few years by the invention of the klydonograph, but the total information available, which has been properly analyzed, is not even half sufficient.

The result of this lack of data and information has been that even where intelligent design was attempted, the actual execution of such design was not at all easy. This, in turn, has had one direct result—trouble, and generally unexpected trouble. Sometimes it takes the form of extensive line flashover, sometimes of extensive line breakage or conductor burning; sometimes it appears as apparatus failure as in transformers, disconnecting switches, or oil switches. But the trouble will always show up ultimately, and when it does occur there is generally a stirring to find out the cause and remedy.

Typical cases of the kind mentioned are undoubtedly known, but perhaps specific cases will bring home the point more clearly. In one case, a 1500-kv-a., three-phase, 132,000-volt transformer stepping down to 33,000 volts failed through a lightning breakdown on the 132,000-volts, volt side. The high tension coils of one of the phases were completely destroyed. This particular transformer received a factory test according to the standard A. I. E. E. Rules, that is, 265 kv. to ground for one minute and also the standard double induced-voltage factory test. This transformer had a lightning arrester installed on the high tension side. In another case a similar transformer located in an entirely different type of country, failed in one phase of the high voltage windings. The breakdown caused a burning of two widely separate parts of the winding. The arc jumped from the winding to ground in one place and from the voltage ratio adjuster to ground in another. This transformer had no lightning arrester installed on the high side. In both of these transformers no damage was done to the bushings. Obviously, therefore, the bushings did not act as any protective gaps for the transformers. Still another case came under observation on a 30,000-kv-a. auto-transformer bank stepping down from 132,000 to 88,000 volts. Four flashovers occurred between the high-voltage and low-voltage bushings within a short time, doing very little apparent damage to the transformer itself, however, but resulting in each case in a very brief service interruption. On the fourth

flashover the corrugations on the low-voltage bushings were broken and the bushing cracked so that it leaked oil and had to be replaced. At the time of the last flashover on this transformer, a klydonograph was on it and the readings showed a potential difference of approximately 850-kv. crest between the two bushings where flashover occurred, and a potential difference of approximately 640-kv. between the corresponding parts of another phase where no flashover occurred. Here was an instance of four cases of trouble without any appreciable visible damage to the transformer. Apparently the bushings acted as excellent protective gaps to the winding.

Instances of trouble on pedestal-type insulators will be cited. In one case a switch insulator on an air-break switch arced over when the charging current of 50 mi. of 132-kv. line was broken through the switch. The same experience was obtained some five months later when the switch was made to perform the same operation.

The history of the Philo-Canton line and the light this has thrown on line insulation practise has already been reported.[3] That this experience is not isolated experience is borne out by the fact that one company this year, after years of operation of a 110-kv. transmission line, has decided to increase the number of ground wires and the insulation on their line.

There are many other cases known which need not be cited. The main thing is, that if operating experience is only investigated far enough, it will be found that there are plenty of data to bear out the fact that there exists ample trouble due to improper insulation strength on our transmission systems, and that this trouble shows up in every phase of the transmission chain. There is bus trouble; there is bushing trouble; there is transformer trouble—for every link in the chain of the transmission system there will be found conditions where breakdowns occurred on that particular link and in many cases the breakdowns occurred on a number of links at the same time.

The difficulty of the situation which generally arises when such a case of trouble occurs is due to the fact that the average transmission system is not a laboratory. Experiments cannot be carried out and the engineer is not allowed, nor should he be allowed, to experiment too widely. The thing that is necessary is to reestablish service, and quickly. The remedy that is therefore applied is chosen from those that can be obtained quickly, and too often the permanency of the cure is in inverse ratio to the speed with which it can be obtained.

What is generally done in a case like that? The apparatus user appeals to the manufacturer, or to a group of manufacturers, for help in the solution of the problem. But it does not follow necessarily that the manufacturer is in a position to give any relief. Often the problem is beyond him, due to the lack of the fundamental data underlying the problem. A part of the blame for this, it is true, rests with the user of the equipment. In the past, equipment has been purchased with practically no attention to its characteristics until operating trouble focuses the attention of the user on those characteristics. The consequence of this has been that in many instances the manufacturer has adopted the attitude that it is a direct reflection on his manufacturing and engineering ability if any question is raised with regard to some of these points, so that today the user finds himself in a position of being unable to get information on characteristics when he asks for it, or to get any sort of guarantee with regard to performance under certain conditions. And yet, if design is to be handled intelligently and if troubles are to be anticipated, all these phases have to be looked into in advance, and that means having the data in advance.

3. *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines,* Sindeband and Sporn, A. I. E. E. Trans., Vol. 45, 1926, p. 770.

IV. Proposed Insulation Chain

If what has been brought up till now has shown anything conclusively, it should be the fact that properly graded insulation values, rather than haphazard values, are vital and necessary under present conditions. The coming to the foreground of interconnection, with the continued expansion of the amounts of power that will be dependent upon transmission and transmission systems for their proper routing and distribution, combined with the higher standards of dependability, make it imperative that this problem, because of its vital importance to such continuity of service, be solved, and quickly.

The problem, which is one of interest to both the manufacturers and the users of electrical equipment involved in a transmission system, is, however, of greater importance to the users and it would appear logical that they should be the proponents of such a movement. For after all there is a large group of manufacturers making equipment involved in the transmission chain, and each individual manufacturer cannot look out for more than his own particular portion. Often, indeed, different departments of a particular manufacturing group are interested only in their own particular parts of a piece of apparatus. The users of the apparatus, however, have to take care of the combined troubles of all of them, and they are therefore the greatest potential losers under a condition where the various portions are not properly correlated.

The writer believes that grading can be accomplished by a proper study and cooperative effort. It is not necessarily simple, but it most surely can be done. There is no doubt of its importance. But yet it has not been done so far.

Undoubtedly one of the causes that have blocked rationalization of insulation in the past has been the fact that the rating of apparatus has been by voltages and very often the voltages were differently divided

on the different classes of apparatus. Further, the rating while probably conforming to A. I. E. E. tests had very little else as a basis for the establishment of the particular rating. It is conceded that the A. I. E. E. test is lacking in many respects since it leaves open to the manufacturer phases of design which have a material effect on its performance on the line. In many cases, as already pointed out, these data are not known even to the manufacturer. Again, one of the causes that has blocked rationalization has been hard economics. To illustrate, if a given 44,000-volt system had to contend in a certain district with conditions of service that were at least as hard on apparatus as a 73,000-volt system in some other district, it is difficult for the designer to bring himself to the point where he will specify 73,000-volt equipment if he is not to appear extravagant, particularly to his executive superiors. Yet in that case, what it is really necessary to specify is insulation strength and not voltage at all.

All this can be overcome by dividing insulation into classes, each class to contain the whole series of links used in the transmission chain and the entire series properly graded. This will be elaborated upon further. The idea, however, is sound. Our experience with 132-kv. system has already been cited. We have had experience with 66,000-volt systems which, while not proving conclusively, indicates fairly well that there is a possibility of designing a system so as to be practically free from insulation troubles.

V. Fundamentals of the Problem

Before considering the detailed analysis of the various insulation classes it might be well to consider the causes of flashover. An insulator will flash over to ground or to another member when the voltage to ground, or to the other member, is greater than the insulating value of the insulator plus the supporting structure from the live point to ground or of the insulator plus intervening space to the other member. Broadly, this covers also cases of puncture. These overvoltages may be of several types and of several sources of origin:

1. A straight overvoltage at the power frequency caused by a system running away, by the crossing of circuits of various potentials, or by some other unusual occurrence.

2. An overvoltage may appear due to arcing grounds. This voltage may have a frequency of the order of thousands of cycles. Except for the isolated neutral systems which are rare today it will, of course, not appear.

3. Overvoltages may take the form of impulse voltages and these, in turn, may be caused either by switching or by lightning.

It has already been shown (1) that where a system is grounded, even with a considerable amount of resistance, the voltage due to an arcing ground can be only of the order of two and a half times the line to neutral voltage. The cases of conditions of overvoltage due to running away of machines, etc., are extremely rare. Excluding, therefore, the cases of arc-overs due to particularly bad local conditions such as particularly bad conducting dust or soot, we get as the principal cause for flashover, impulse voltages. The switching surges will, at the maximum, be of the order of five and

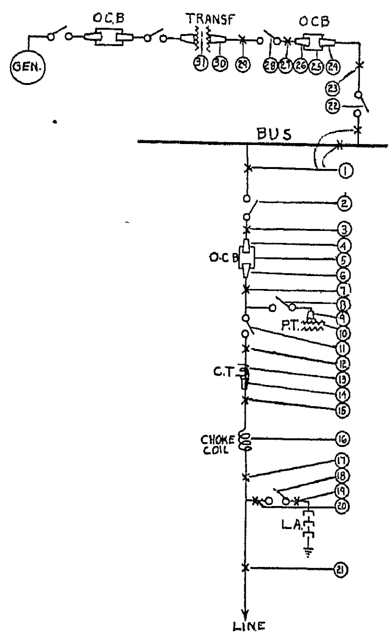

Fig. 2—Typical High-Voltage Station

1 Bus and bus tap insulators
2 Disconnect on bus
3 Insulator—line side bus disconnect
4 O. C. B. bushing—bus side
5 Oil circuit breaker
6 O. C. B. bushing—line side
7 Insulator—line side O. C. B.
8 Disconnect—on P. T.—line side O. C. B.
9 Bushing on P. T.
10 Potential transformer
11 Disconnect—line side O. C. B.
12 Insulator—line side O. C. B. disconnect
13 Current transformer
14 Bushing on C. T.
15 Insulator—lineside C. T.
16 Choke coil
17 Insulator—lineside choke coil
18 Disconnect on L. A.
19 Insulator on sphere-gap
20 Insulator on L. A. tap
21 Line insulator
22 Disconnect on bus
23 Insulator—O. C. B. side disconnect
24 O. C. B. bushing—bus side
25 Oil circuit breaker
26 O. C. B. bushing—transformer side
27 Insulator—transformer side O. C. B.
28 Disconnect — transformer side O. C. B.
29 Insulator—transformer side disconnect
30 Power transformer H. T. bushing
31 Power transformer H. T. winding

one-half times normal, but voltages so high will be very rare, which means again that the principal high voltages to insulate for are the voltages due to lightning.

Let us consider a power system transmission chain, list all the apparatus and equipment and, if possible, see whether or not a definite system of grading cannot be worked out for the various insulation members.

In Fig. 2 there is shown in diagrammatic form the various portions of such a chain. Fig. 2 as it stands, is representative of a typical high-voltage generating station with a generator and a transmission line connected to the bus. It will be seen that some of the parts have been rather finely subdivided in Fig. 2, the reason being that it was thought that, in the first analysis, it would be best to go the limit in the subdivision of parts, and later consolidate such members as could be placed in the same class.

If the generator shown on the low side of the transformer in Fig. 2 is taken away and a low-voltage bus substituted for it, then Fig. 2 becomes the typical diagram for a combination switching and stepdown substation, and if the entire upper half of the diagram is taken away, Fig. 2 becomes a typical switching station diagram.

Before a complete analysis and solution of the problem is possible, it will be found necessary to have further data:

1. It will be necessary to have definite power-frequency flashover values. The methods of obtaining these values should be more rigidly prescribed than at the present time. The methods of measuring at the present time are not rigidly enough prescribed and too great variations in the values of practically identical apparatus exist in the figures of different manufacturers.

2. It is necessary to have definite data on the lightning flashover. In this connection it is essential that a standard lightning wave be established at present. Until complete and exhaustive studies with the Dufour oscillograph show definitely what lightning is, it is essential, if confusion is to be avoided when the lightning or impulse flashover is discussed, that it mean a definite thing. This will clear up the present situation where each manufacturer or each laboratory man is his own lightning maker, and utilizes his own ideas as to what constitutes a lightning or impulse wave. A method of measuring this particular wave should be definitely agreed upon. If so much is accomplished, it should be possible to go one step further and reach a definite understanding with the manufacturers that such data are necessary for design and that they agree to furnish such data to the users of their equipment.

3. More work will have to be done on the characteristics of switching surges. Numerous data are available now with regard to the magnitude of switching surges but further data are needed with regard to their frequency or their characteristics, and as to whether their effect on insulation approaches more closely to that of lightning or impulse wave, or more closely to the power frequency.

4. More data are necessary on the protective features of the design of the stations themselves and particularly on the protective effects of various possible incoming line arrangements, of arrangements of apparatus with regard to structure, and on the protective values of lightning arresters.

TABLE V

RATED RELATIVE IMPORTANCE OF APPARATUS ON LIGHTNING VOLTAGE CONSIDERED FROM POINT OF VIEW OF

A. Minimum number of interruptions
B. Minimum danger of complete interruption
C. Minimum cost of repairing damaged apparatus

PROPOSED GRADING—STRONGEST INSULATION (1) TO WEAKEST (31)

Columns 1 Order of insulation strength	H. T. Generating station			H. T. Switching station			Step down & switching station		
	2 A	3 B	4 C	5 A	6 B	7 C	8 A	9 B	10 C
1	21	1	31	21	1	5	21	1	31
2	20	2	25	20	2	10	20	2	25
3	18	22	5	18	3	13	18	22	5
4	19	3	10	19	4	4	19	3	10
5	17	23	13	17	5	6	17	23	13
6	16	4	30	16	6	9	16	4	30
7	15	24	24	15	10	14	15	24	24
8	14	5	26	14	13	1	14	5	26
9	13	25	4	13	9	2	13	25	4
10	12	31	6	12	14	11	12	31	6
11	11	30	9	11	7	8	11	30	9
12	8	26	14	8	8	3	8	26	14
13	9	28	1	9	11	7	9	28	1
14	10	29	22	10	12	12	10	29	22
15	7	27	28	7	15	15	7	27	28
16	6	6	2	6	16	16	6	6	2
17	5	13	11	5	17	17	5	13	11
18	4	14	8	4	20	20	4	14	8
19	3	10	23	3	18	18	3	10	23
20	2	9	27	2	19	19	2	9	27
21	1	8	29	1	21	21	1	8	29
22	22	7	3				22	7	3
23	23	11	7				23	11	7
24	24	12	12				24	12	12
25	25	15	15				25	15	15
26	26	16	16				26	16	16
27	27	17	17				27	17	17
28	28	20	20				28	20	20
29	29	18	18				29	18	18
30	30	19	19				30	19	19
31	31	21	21				31	21	21

VI. Proposed System of Grading

In Table V there has been set up a proposed system of grading for every member shown in Fig. 2, considered as a generating station, as a straight switching station, and as a step-down and switching station. In the setting down of orders of importance certain assumptions have been made. These are as follows:

1. That the station has two buses.

2. That there is a transfer or inspection oil switch available at the station.

3. That in case of a lightning impulse or discharge coming into the station, which is sufficiently high to spill over, the spilling over at one point or on one piece of apparatus will prevent the impulse with a dangerously high head going any further; that the first spillover would afford sufficient relief, and that the rest of the equipment beyond that point would not be subject to spillover.

4. The effect of a change in the entrance arrangement of ground wires, the effect of the protective values of the bus structure itself, and the effect of the lightning arrester have been entirely neglected. This may be unfair to the lightning arrester, perhaps, but it was felt that for the purpose of the study it would be best to consider the lightning arrester as an additional

safeguard, rather than as a means of definitely reducing the value of the impulse voltage to which apparatus may be subjected.

Referring again to Table V, columns 2, 3, and 4, consider the high-voltage generating station from viewpoints A, B, and C. In the case of viewpoint A it has been assumed that the source of the high-impulse voltage is the transmission and that it becomes lower as it travels into the station. This, of course, takes no account of reflections and re-reflections but it is necessary to do that if the problem is to be considered at all. Viewpoint B is based on the assumption that if an insulator on the bus fails a complete interruption will result. The installation of bus sectionalizing switches, however, results in no such complete interruption. In that case, however, instead of considering the bus as a whole, if the problem is confined to a particular bus section the assumption just made still holds true. In C it has been assumed that the most expensive piece of apparatus to repair on failure is the power transformers and that in general when an oil-filled piece of apparatus such as the current or potential transformer, is damaged, then it will generally be a more expensive matter to repair than the damage to a mere insulator on the disconnect switch.

With these assumptions known, it is plain why, in the case of column 2, the highest insulation value has been assigned to the member 21, and the lowest to member 31. In the case of column 3 on the other hand, it can be seen why the highest insulation strength has been assigned to member 1 and the lowest to member 21. In the case of Column 4, the highest insulation strength has been assigned to member 31 and again the lowest strength to 21. It is not believed necessary to go into a detailed explanation of the reason for the relative order of the intervening members as it is felt with the explanation of the assumptions and the basis of reasoning employed the remaining positions will be obvious upon study. Columns 5, 6, and 7 analyze the order of insulation strength for a switching station from the viewpoints A, B, and C respectively, and Columns 8, 9, and 10 show a proposed grading system for a combined step-down and switching station from the same points of view also, that is from points A, B, and C.

Examining Table V a little more carefully, one will see that the order of grading for a particular point of view is not very different for the various stations; that is, it is practically the same for the generating station as for the switching station, and altogether the same for the generating station and the combined step-down and switching station. Obviously Table V does not offer, as it stands, a practical setup. There are altogether too many members and it is not conceivable that a grading system could be worked up with 31 members and yet have a practical difference in insulation values between them. In Table VI the total number of 31 members has been reduced to 15 and values assigned to each member on the basis of its position in Table V. These are shown on columns 1, 2, and 3. In column 4 the position numbers of a particular member in columns 1, 2, and 3 has been averaged and on the basis of that average a suggested arrangement for general conditions has been worked out in column 5.

An inspection of column 5 reveals an interesting setup. It shows that from the standpoint of general minimum disturbance and minimum damage to the system, the internal make-up of the oil switch ought to be the strongest, that the bus insulators ought to come next and the power transformer windings next, the oil switch bushing next in strength and so on until we get to the insulation of the gaps on the lightning arresters which ought to be lowest down in the series. It shows further, for example, that in general the power transformer bushings ought to occupy a place two-thirds down toward the low end of the insulation chain as against the first position that they undoubtedly occupy on many systems today. It shows that while the line insulators are not to be the very lowest in insulation value they should be very close to that, their position in

TABLE VI
GRADING INSULATION FOR LIGHTNING IMPULSE SURGES
1 = Highest insulation down to 15 = Lowest Insulation for Results Indicated

Column / Member	Apparatus	1 Min. no. of interruptions	2 Min. danger of complete interruptions	3 Min. cost of apparatus repair	4 Ave. position from columns 1—2—3	5 Suggested for general conditions
A	Oil switch (internal make-up)	13	4	2	6-1/3	1
B	Insulators—Bus side of oil switches	10	1	9	6-2/3	2
C	Power transformer windings	15	5	1	7	3
D	Oil switch bushings	12	3	6	7	4
E	Potential transformer windings	9	9	3	7	5
F	Disconnects—Line side of oil switches	3	7	11	7	6
G	Insulators—Line side of oil switches	2	8	12	7-1/3	7
H	Current transformer windings	7	11	4	7-1/3	8
I	Disconnects—Bus side of oil switches	11	2	10	7-2/3	9
J	Power transformer bushings	14	6	5	8-1/3	10
K	Potential transformer bushings	8	10	7	8-1/3	11
L	Current transformer bushings	6	12	8	8-2/3	12
M	Insulators on line	1	15	15	10-1/3	13
N	Choke coils	5	13	13	10-1/3	14
O	L. A. sphere-gap insulators	4	14	14	10-2/3	15

the table where the lowest value is represented by 15, being 13. Finally this establishes in general an order of insulation strength from which some practical setup can be made.

This has been done in Table VII. Here the 15 members of Table V have been consolidated into four groups and it will be noticed that the grouping in Table VII follows almost entirely the order indicated in Column 5 of Table VI, the one exception being that of the insulation of the line itself. Table VII then proposes that the insulation on a transmission system should be divided into four groups and that the insulation of these groups follow a definite order,—that the insulation of the oil switches and the bus should be highest and the insulation of the line should be lowest. (By line insulation is meant of course only that portion of the line which can be considered from the standpoint of the substation itself. Obviously the insulation of the remainder of the line is an independent problem in economics. If sufficient money is spent, sufficient line insulation can be provided to prevent even the highest lightning voltage from flashing over. This phase is of course not considered here.) Table VII further suggests that the insulation of a group of members in the transmission system consisting of oil switch bushings, potential transformers, disconnect switches, current transformers, etc., be all held at the same level. These four groups are subsequently referred to as the four links.

TABLE VII
PROPOSED INSULATION CHAIN

Rationalized order of insulation Col. 5-Table VI	Apparatus	Suggested order of links in chain
1	Oil switch internal make up	1
2	Insulators—Bus side of oil switch	
3	Power transformer windings	2
4	Oil switch bushings	3
5	Potential transformer windings	
6	Disconnects—Line side of O. S.	
7	Insulators—Line side of O. S.	
8	Current transformer windings	
9	Disconnects—Bus side of O. S.	
10	Power transformer bushings	
11	Potential transformer bushings	
12	Current transformer bushings	
14	Choke coils	
15	L. A. sphere gap insulators	
13	Insulators on line	4

SUBDIVISION OF LINKS

1 A—Oil switch (exclusive of bushings)
1 B—Bus insulators—(suspension or strain)
1 C—Bus insulators—(Post type)
2 A—Power transformers (exclusive of bushings)
3 A—Bushings and disconnects
3 B—Transformers (C. T. & P. T.)
4 A—Short section of line nearest S. S. (About 1 mile).

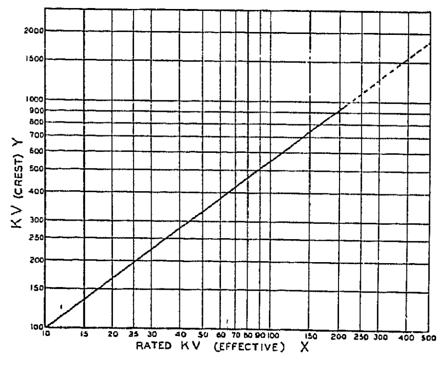

FIG. 3—TRANSMISSION LINE INSULATION BASED ON PRESENT PRACTISE $Y = 18.3\, x^{0.742}$

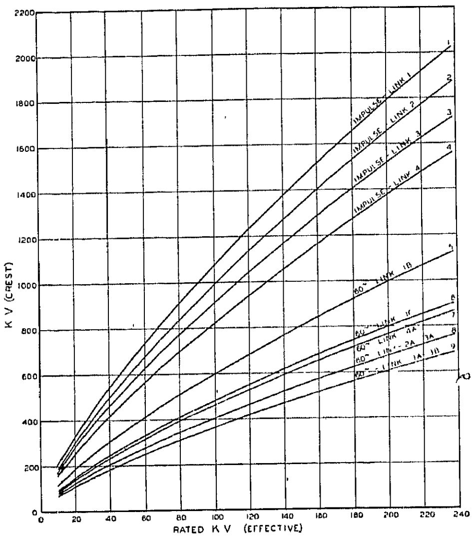

FIG. 4—PROPOSED GRADING OF TRANSMISSION SYSTEM INSULATION STRENGTHS

Showing impulse and 60-cycle flashover or breakdown voltages. For references to links, see Table VII

VII. PROPOSED INSULATION SYSTEM

In Fig. 3 the data of curve No. 6 of Fig. 1 have been plotted on logarithmic coordinates and a balanced straight line drawn through the values. The equation of this line is

$$Y = 18.3\, x^{0.742} \qquad (1)$$

where Y = the crest value of flashover in kv.,

and x = r. m. s. of the line voltage in kv.

The same curve is plotted on regular coordinates as curve 13 in Fig. 1. Using an impulse ratio of 1.8 we get curve 14 in Fig. 1 as the impulse flashover value of line insulators for average present practise. The equation of this curve is

$$Y_i = 32.9\, x^{0.742} \qquad (2)$$

Where Y_i is the impulse value and all other values are the same as in equation (1).

In Fig. 4 curves No. 1 to 4 have been proposed for grading the four links shown in Table VII. These curves represent the breakdown or flashover values of the various links and are based on the following:

a. Starting out with curves No. 4 as 100 per cent the other curves have been raised by 10 per cent in terms of curve No. 4 so that curve No. 1, for example, represents at every point 1.3 times the values in curve No. 4.

b. The line insulation developed in Fig. 3 and shown as curves 13 and 14 in Fig. 1 has been adhered to for the insulation of that portion of the lines affecting the substations. On the assumption that a 20 per cent differential would be allowed between the insulation of the line adjacent to the substation and the insulation of the line proper this made curve 14 of Fig. 1 and curve 2 of Fig. 4 identical.

c. Curves 1 to 4 in Fig. 4 do not take into account 60-cycle strengths or tests.

The development of 60-cycle strength has, however, been carried out in curves 5-9. These are based on the impulse strength shown in curves 1-4 and the relationships are as follows:

Curves 9, 5, and 6 give the 60-cycle strength of link 1, parts A, B, and C respectively.

Curve 8 gives the 60-cycle strength of link 2.

Curves 8 and 9 give the 60-cycle strength of link 3, parts A and B respectively.

Curve 7 gives the 60-cycle strength of link 4.

The values of 60-cycle strength are based upon the best available information at the present time on impulse ratios. Where the 60-cycle strength of a particular link has been split into two or more parts, this was done because the different members naturally had different impulse ratios. This clearly shows up the fact that while rationalization is possible for insulation value on the basis of lightning strength and while it may be possible to reduce the number of links in an insulation chain to as low a value as 4, as soon as 60-cycle strength is considered the problem becomes more complicated, the reason being, of course, the different impulse ratios of the different classes of material. The

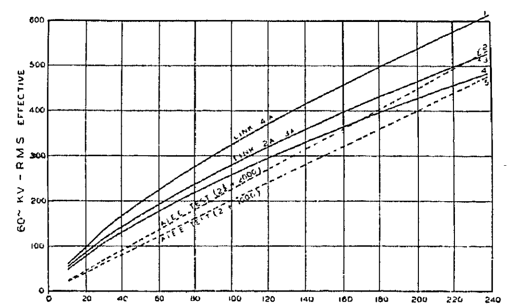

FIG. 5—60-CYCLE EFFECTIVE VOLTAGE BREAKDOWN OF LINKS AND A. I. E. E. TEST SPECIFICATIONS

determination of the ratios employed will be evident from an inspection of the curves.

In Figs. 5 and 5A the curves of 60-cycle strength developed in Fig. 4, have been transposed and plotted in terms of r. m. s. values on both coordinates. The A. I. E. E. tests corresponding to apparatus represented by link 3-A are shown in curve No. 2 (dotted) by links 2-A and 3-B in curve No. 5, by links 1-A and 1-C in curve No. 8, and by link 3-B in curve No. 10 (dotted). In analyzing these curves it will be seen that while it is possible to rationalize and to work out a system of insulation strength with comparatively few links in a particular chain the problem is not quite as simple when the 60-cycle strength is considered. Further, it is definitely clear that in so far as present A. I. E. E. tests are concerned, the buying and specify-

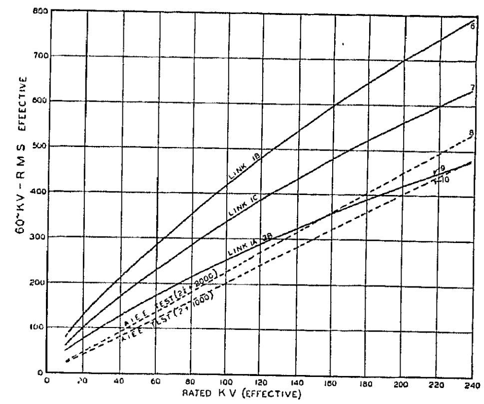

FIG. 5A—60-CYCLE EFFECTIVE VOLTAGE BREAKDOWN OF LINKS AND A. I. E. E. SPECIFICATIONS

ing of equipment on the basis of these tests will result in a system of insulation that is far from rational as far as impulse or lightning strength is concerned. It shows again that if a system such as proposed in Fig. 4 were adopted, in voltages up to approximately 150 kv. a considerable increase in 60-cycle strength and test is necessary if the proper impulse strength is to be obtained on equipment such as transformers. This may appear objectionable and will naturally be raised as an argument against the system but the objection is valid only so long as present systems of design are followed. As soon as it is definitely recognized that strength in two directions is required, the designer of equipment will be in a much better position than he is today, for he will be able to design for requirements of actual line service rather than along the present lines, where he designs for one thing, *i. e.*, 60-cycle strength, whereas what is needed is impulse strength.

A thorough revision of the standards with regard to 60-cycle strength and 60-cycle tests, will be necessary before complete rationalization can be accomplished. No attempt will be made to attack this particular problem at this time. Leaving, however, the 60-cycle tests as they are, it should still be possible to work up a rationalized system of insulation strength under impulse conditions and it should be unnecessary, if the system is a proper one, to disturb it in any way when finally the 60-cycle end is rationalized.

Keeping this in mind, the writer suggests the system shown by curves 1 to 4, Fig. 4, as fulfilling the necessary requirements. Mention has previously been made of the fact that as long as apparatus and insulation strength are specified and bought on the basis of

normal or line voltage, difficulty will be encountered in utilizing on a system of a definite voltage, apparatus that might have a nominal rating of a considerably higher voltage. This difficulty could definitely be avoided if apparatus were bought on the basis of normal operating voltage and with insulation strength of a certain definite chain. To amplify: suppose, referring again to Fig. 4, a series of insulation chains were drawn up as shown in Table VIII. This table offers a series of insulation chains for every one of the four links, with chains spaced at proper intervals. The table suggests for the present operating range from 25 kv. and upwards, a series of 10 chains, but this number could be cut by one or two or, perhaps, increased by a similar number. The point is that chain No. 4, for example, might be a perfectly suitable insulation chain for a system operating at 69,000 volts in California, for instance, but in another territory, say in Florida, a much better chain for the same operating voltage might be chain No. 5. If once the idea is embraced that insulation strength does not always go together with operating voltage and insulation is specified independently of operating voltage, then it will be possible to realize the ideal of obtaining, for each system, the insulation strength really necessary. In Table VIII nominal kilovolt classes have been purposely indicated but there is really no valid reason why these should be adhered to or why these should appear in any specifications or in any of the design calculations.

TABLE VIII
IMPULSE VOLTAGE FAILURE FOR PROPOSED INSULATION CHAINS

Insulation chain no.	1	2	3	4	5	6	7	8	9	10
Nominal kv. class	25	37½	50	70	90	115	145	175	205	237½
Link no.	All values below in crest kv.									
1	382	526	639	819	985	1185	1405	1620	1830	2020
2	353	486	592	756	910	1095	1296	1495	1686	1870
3	324	445	542	693	834	1005	1190	1370	1548	1715
4	294	405	492	630	757	912	1080	1245	1405	1555

VIII. Practical Application of System and Results Expected

If a system of insulation such as proposed in Table VIII or a similar system were adopted, it would result in benefits in many directions. Among these are:

1. The problem of designing the insulation for a system would be considerably simpler than it is at present. Once having decided on the insulation strength necessary on one of the important links, the particular chain into which the entire system insulation is to fall would be determined automatically. The problem of specifying the insulation for the various pieces of apparatus would then become one of simply specifying a certain definite insulation chain.

2. From the purchasing of apparatus standpoint it would mean the placing of the various manufacturers on a more even competitive basis. It would give greater assurance of getting the best purchase for a given amount of money.

3. The establishment of a definite number of classes will result in simplifying and reducing the number of insulating units and insulating classes offered, and will therefore result in a reduction of cost with benefits both to the manufacturer and to the user of apparatus.

4. Without treating every substation insulation problem as a special problem to be long studied, it would be possible to get a correct solution and one that would be reasonably certain to work right under practically all conditions in so far as insulation is concerned.

5. The final effect of all the above would be a great improvement in the type of service rendered by the transmission system.

IX. Summation

The problem of rationalizing the transmission system insulation is greater than can be covered within the scope of one paper. The writer believes, however, that he has shown that:

1. The present status with regard to insulation practise and standards is not satisfactory. This is as true with regard to the manufacturing of apparatus, the application of apparatus, as it is with regard to the various rules and regulations issued by state and other regulatory bodies.

2. There is no single cause for the present situation, but there are many contributory factors, some of which were perhaps unavoidable.

3. The net effect of the present status is one of confusion in regard to the specification and the purchase of insulation value. Further, the problem of designing a system that is properly correlated in insulation strength is extremely difficult. This results, in the long run, in more trouble on the transmission system than is necessary or desirable.

4. It would be highly desirable to bring about a condition where some of these difficulties could be eliminated without making a separate research problem of each problem of transmission. If a system of grading were worked out and adhered to by all the manufacturers and by all the users of apparatus and equipment, many of the difficulties that are encountered today in the problem of making the transmission system give continuous service would be done away with.

5. Before such a state can be reached it will be necessary to obtain considerably more information or data bearing on the problem. It will be necessary to have more exact data with regard to the characteristics of switching surges and of lightning waves, and a definite agreement as to how these various quantities are to be measured,—in other words, standards for each.

6. Assuming that all the data outlined in 5 are

obtained, a method of arriving at the order of grading of insulation can be formulated. A specific system was actually worked out. It is possible by proper consolidation of various members to reduce the links in a transmission chain that will be graded from each other to a reasonable number. A system composed of four links was proposed. While four links are adequate from a lightning standpoint, from the power frequency standpoint the problem is considerably more complicated due to the different impulse ratios. This problem will require further study.

7. Without changing for the present the specifications covering power frequency strength, a series of insulation chains can be worked out that will be properly graded from the standpoint of lightning strength. A definite series of that type was proposed. By elimination of nominal operating voltages the probability of obtaining proper insulation strength will be enhanced in many cases.

8. If the systems proposed are adopted the ultimate result ought to be less expensive and more satisfactory design, in other words, better continuity on the transmission system as a whole.

Acknowledgment is due to Mr. I. W. Gross for his help in preparing some of the data and in drawing up the numerous charts and tables.

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Discussion

RELATION BETWEEN TRANSMISSION-LINE AND TRANSFORMER INSULATION

(LEWIS)

RATIONALIZATION OF TRANSMISSION-SYSTEM INSULATION STRENGTH

(SPORN)

NEW HAVEN, CONN., MAY 9, 1928

V. M. Montsinger: The authors of these papers have pointed out the desirability of setting up standards for grading the various apparatus according to their impulse-voltage strengths and have shown the haphazard way in which this work has been done in the past. Their plea for a more rational method should receive very careful consideration.

I do not believe that there is any argument as to whether or not the relative values of the insulation of transformers and the various adjacent apparatus should be put on a more rational basis. The important question is how shall the grading be done? There are two phases to this problem. First, what should be the difference between, say the transformer impulse strength and the arc-over strength of the adjacent line insulation, etc.; and second, what is the most convenient and practical method of expressing the impulse strengths or the relative strengths of the various apparatus?

It is from the second standpoint only that I wish to discuss these two papers. I shall for the sake of simplification confine my remarks to transformers and adjacent line insulators.

Naturally, the first thing that the operating engineer asks for is the impulse breakdown values of the transformer windings and the flashover values of bushings and line insulators. It is, of course, well known that the impulse breakdown of insulations, either of solids, oil, or air, is dependent entirely on the kind of wave used and whether breakdown occurs on the rising front at the crest or at some point beyond the crest, generally called the tail of the wave. Therefore, for the impulse strength to mean anything at all it is necessary to define the wave. A standard wave, of course, could be set up but it would mean that everybody who desired to make a test must have the same kind of a lightning generator, which of course is impractical. Furthermore, it is not practical to test a transformer winding with impulse voltage to check its impulse strength. Neither is it desirable to subject a winding to an impulse voltage in value anywhere near its failure point on account of the possibility of causing injury which might not show up until after being placed in service. Therefore, it appears that we must look for some other more satisfactory method.

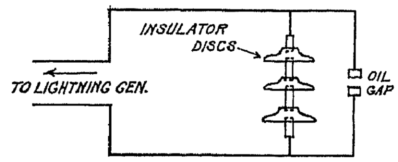


FIG. 1—SET-UP FOR COMPARING BREAKDOWN OF OIL AND ARC-OVER OF DISKS ON FRONT AND TAIL IMPULSE WAVE

Let us consider first the adjacent line insulators and their characteristics with respect to impulse flashover at different points on the wave. Tests conducted with Mr. Peek's lightning generator have shown that within practical limits the flashover impulse ratio of an insulator varies with different waves in about the same order as does the breakdown of insulations.

To illustrate what I mean a typical case will be given. Fig. 1 herewith shows an oil gap shunted with three standard 10-in. disks. When an impulse voltage, whose maximum value was approximately twice the flashover value of the insulators, was imposed, the disks naturally cut off the wave, provided the oil-gap setting was not too close. The oil gap was then adjusted to cause one-half of the breakdowns to occur across the oil gap. Sphere gap measurements showed that the disks limited the wave to about 600 kv. The oil gap was then widened and the imposed wave lowered until flashover did not occur until a point beyond the crest of the wave had been reached. To cause one-half of the breakdowns to occur across the oil gap the electrode had to be brought back to practically the same setting as before. The maximum value of the wave in this case was around 450 kv. as determined by sphere gaps. The time in the two cases ranged from a fraction of a micro-second to several micro-seconds. Similarly the same phenomenon was found when solid insulation was used in place of the oil gap.

This, of course, means that a string of insulators can be used as a yard stick for comparing or expressing impulse strengths of transformer windings. Or, in other words, if we know the proper relation between the impulse strength of a given number of line insulators and a given voltage transformer, it is not necessary to know or to give the impulse values of either.

Furthermore, it would eliminate the necessity of defining the wave, for the reason that if the proper relationship is known on one part of the wave approximately this same relationship holds for another part of the wave. Of course, there is a limitation to this in that the two curves of impulse strength versus time are not exactly parallel but cross and diverge as the waves approach the 60-cycle peak value as shown in Fig. 2 herewith.

If all insulator disks had the same spacing it would be satisfactory to express normal line insulation in terms of the number of disks. However, since the spacing of disks may vary considerably, some being as low as 4¾ in., while the standard spacing is 5¾ in., and since both the 60-cycle and impulse flashover strengths of a string of insulators is within reasonable limits a function of the vertical height, and furthermore since both the dry and wet impulse strengths are the same, it is entirely practical to express line insulation in terms of 60-cycle dry arc-over values. This enables any manufacturer or operating company to check the tests.

Referring to the recommended line insulation in Table IX of Mr. Lewis' paper, it will be noted that the 60-cycle arc-over is considerably higher than the 60-cycle tests on the transformer corresponding to twice line voltage plus 1000 volts. This does not mean from the standpoint of impulse voltages the arc-over of the insulator is stronger than the transformer windings, for the reason that the impulse ratio of breakdown of air is considerably less than the impulse ratio breakdown of transformer windings. This difference plus the factor of safety between the tests and actual breakdown of windings makes the transformer stronger

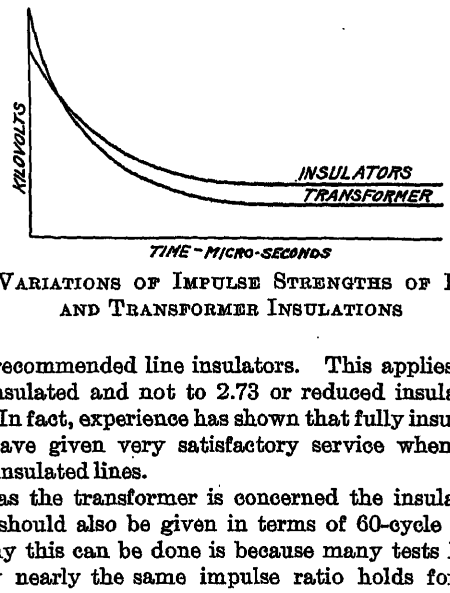


FIG. 2—VARIATIONS OF IMPULSE STRENGTHS OF INSULATORS AND TRANSFORMER INSULATIONS

than the recommended line insulators. This applies, of course, to fully insulated and not to 2.73 or reduced insulation transformers. In fact, experience has shown that fully insulated transformers have given very satisfactory service when used with normally insulated lines.

So far as the transformer is concerned the insulation in the windings should also be given in terms of 60-cycle tests. The reason why this can be done is because many tests have shown that very nearly the same impulse ratio holds for oil alone, puncture of solid, puncture of combinations of oils and solids, creepage over solids, and finally, breakdown of transformer windings, either of interleaved type or concentric type. It is indeed fortunate that this is so; otherwise, if the different insulations and different arrangements of insulation gave widely different impulse ratios it would be an impossibility to express the impulse strength in terms of 60-cycle tests. Not only should it be expressed in terms of 60-cycle voltage but the transformers should be so tested. This makes it possible for all manufacturers to be on a fair and comparable basis and assures the customer of what he is getting.

The impulse strength of the transformer bushings and terminals can be expressed also in terms of 60-cycle dry flashover if it is desirable to grade its impulse strength in reference to that of the other apparatus.

In summing up, the main point which I wish to bring out is that it is not practical and, in fact, not necessary to attempt to give impulse values for the strength of transformer windings and the impulse flashover values of bushings and insulators, but that the desired purpose is accomplished in a more satisfactory manner if 60-cycle dry flashover values of insulators can be standardized as the yard stick for judging the impulse strength of the transformers.

W. L. Lloyd, Jr: The subject of rationalization of insulation is not a new one. However, the limited knowledge available (for example, *The Effect of Transient Voltgages on Dielectrics*, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXIV 1915, Part II, p. 1857) has not been utilized as fully as its importance warranted.

Developments have been rapid in the last few years due to a realization that lightning is not a mysterious phenomenon, but that it is a definite thing that can be discussed in an engineering way, studied in the laboratory, and guarded against in the field.

As has been pointed out in the papers, laboratory work and field experience in general show that it is important to design a line so that the conductors are as near to the ground as possible, and that high towers and badly exposed places should be avoided. Similarly, horizontal spacing is preferable to vertical spacing since the average lightning voltage induced on the line is less with horizontal spacing.

Ground wires properly installed and longer insulator strings out on the line can be employed to eliminate flashovers or to reduce their number. Grading-shields or grading-rings on the insulator strings, by raising somewhat, in effect, the lightning sparkover voltage of the insulator string, can be utilized to reduce further the number of flashovers, and prevent damage to the insulators when a flashover occurs.

Long insulator strings should not, however, be brought right up to the station. For a half mile or so from the station recommended insulation should be employed to limit the lightning voltages impressed upon the station equipment. Where dirt or leakage conditions are bad in the vicinity of the station the lightning voltage applied to the station equipment can be more satisfactorily limited by low-set rings on the long insulator strings or by a short air-gap in parallel with the string. To prevent an excessive number of flashovers across these shorter insulator strings, low-set rings, or paralleled gaps, the number of ground wires should be increased over this short section of the line. The proper number of ground wires will give the same factor of safety on this short section of the line with reduced insulation as on the main section of the line with increased insulation but with fewer ground wires. Lightning arresters, if used, should be placed as close to the transformers as possible. The transformer insulation should be stronger than the sparkover voltage of the bushings or the protective gaps at the station.

As suggested by Mr. Montsinger, the strength of the transformer, the sparkover of the bushings, the setting of the gaps, and so forth, should preferably be expressed in terms of the sparkover voltage or number, of standard 10-in. diameter, 5¾-in. spaced, insulator disks, since then any discussion of the shape of the wave, when sparkover takes place, and so forth, does not enter. In this way the laboratory work should be most advantageously utilized by the largest number of operating engineers and we can, at last, proceed with a logical and rational insulation of our transmission systems as we have been attempting to do for so many years and as urged again by Mr. Sporn.

C. L. Fortescue: Recent investigations both in the field and in the laboratory indicate that the lightning surge is of appreciable duration. It is estimated that the duration of the effective portion of the wave may vary from a few to 100 microseconds, the longer wavelength having crest values below the 60-cycle flashover of the insulators. Mr. Torok's investigations on the phenomenon of flashover between sphere gaps shows that the speed of propagation of the streamers from sphere to sphere is of the order of one-tenth the velocity of light. Similar tests in connection with strings of insulators indicate a speed of propagation over the length of the string of the order of one-fiftieth the velocity of light. These figures are necessarily ap-

proximate and may be subject to modifications as a result of further investigation. However, the results indicate that the time required to complete a flashover due to a surge, after the 60-cycle flashover point has been reached, is, for a string of insulators, of the order of a fraction of a microsecond. Fig. 3 herewith shows the impulse flashover of a string of five standard units and of a string of fourteen standard units for lightning surges of different steepnesses of wave front. The figures are approximate and subject to modification due to further knowledge obtained in the laboratory. We deduce from our laboratory investigations that any lightning wave whose crest reaches the 60-cycle value and exceeds it for a fraction of a microsecond will cause flashover of the insulator string.

The importance of impulse factor to various steepnesses of wave front lies in the fact that the surge potential from a lightning stroke would reach extremely high values if it were not for the flashover limit imposed by the insulator string itself. As a consequence, before the lightning surge has had time to reach anywhere near its crest value it is chopped, or discharged, by

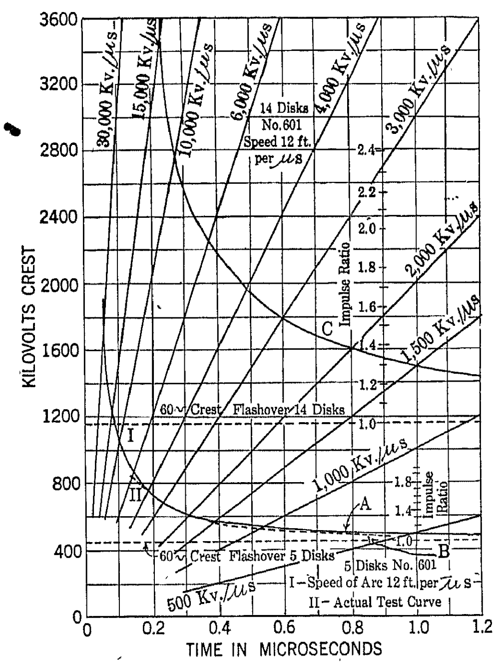


Fig. 3—Voltage Time Flashover Curves of Suspension Insulators

the flashover of the insulator string. It is interesting to note that even before the string has reached the flashover point, as indicated by the complete formation of the streamer along the length of the string, the conductivity over the string has increased enormously, so that the leakage current over the string, even before the actual flash takes place, is sufficient to reduce materially the potential of the surge before flashover occurs. When the insulator flashes over, the surge impedance at that point of the line is reduced to practically zero. Consequently, the remaining portion of the lightning surge is reduced to low potential and only the portion of the wave up to the flashover point passes over the line. This portion now is of relatively short duration as compared to the original lightning surge from which it is evolved, and may have a crest value several times the 60-cycle flashover of the insulator string. These chopped waves are of importance because they have this high crest value and may be a source of danger to the apparatus connected to the line.

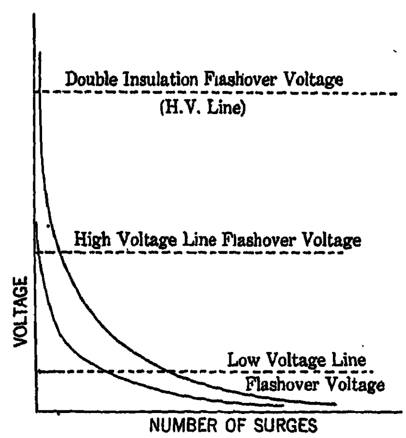
There seems to be a rather widespread misconception of the part played by the time lag of the insulator string in the operation of transmission lines. There seems to be an idea that high impulse factor increases the effective insulation of the line against lightning surges. Many recent tests indicate that any surge due to lightning which goes slightly over the 60-cycle flashover value of the insulator string will cause a flashover. If this be the case, the less the time lag, or the quicker the flashover, the less will be the severity of the surge impressed on connected apparatus. Furthermore, the time lag of an insulator string leads to an undesirable characteristic, namely, the tendency of a string of insulators to cascade. Fortunately, due to the fact that there is this large time lag in the flashover, we are able to make use of an auxiliary device, namely, the arcing ring, which when properly designed will, by improving the field of the insulator, increase the resistance of the string itself to the 60-cycle voltage, and consequently the tendency to flashover may be delegated to the arcing rings themselves which have probably a somewhat lower time lag than the insulator string. This can be done without sacrificing the 60-cycle flashover value of the string itself without the rings. In this way when flashover occurs the arc will form between the arcing rings and no cascading will take place over the string of insulators and as, in general, the power arc will follow the path of the impulse flashover, the use of arcing rings of proper design insures the insulator string against breakage due to cascading. The arcing ring, therefore, has two desirable characteristics: first, it prevents cascading of the string and, secondly, it tends to reduce the impulse factor for a given steepness of wave front. In other words, it gives to the insulator string flashover characteristics more nearly approaching that of spheres.

I should like to bring forward a broader point of view in considering the insulation of transmission lines. It is customary to consider the problem of transmission-line design in two aspects, namely insulation and protection. In the design of apparatus two methods may be used, one might be entitled the method of brute force, and the other the method of properly protecting the various parts so as to distribute the electric forces in the most favorable manner. We do not differentiate between these two methods and describe one as insulation and the other as protection. I feel that the progress in the design of transmission lines has suffered by considering these two aspects independently. As a result, controversies arise due to transmission engineers considering only one of these aspects instead of looking at the problem from the broad point of view. To illustrate this point, let us suppose we have a 220-kv. transmission line insulated with 14 units and we find that with these 14 units the number of outages per 100 miles per line amounts to a certain definite figure, and we wish to reduce this figure to some desirable value. There are two ways in which this may be done. We find that following the one way, which we will designate the method of brute force, we would require an insulator string with perhaps 28 units. This, of course, would mean that the towers would have to be raised at least 6½ ft., the necessary amount depending upon the design of the tower structure. This would in addition involve strengthening the tower to meet the increased stresses due to the added height. The second method would involve adding two ground wires in the proper position over the transmission line, the ground wires having at least one layer of good conducting material and being properly suspended so as to insure against mechanical breakage. Fig. 4 herewith shows that the effect of the ground wires as far as the outage is concerned, is the same as that due to doubling the length of the strings. This conclusion is based on an assumed reduction in the surge potential, due to the ground wire, of 50 per cent. This figure is believed to be conservative. Mr. Peek has obtained much higher values in laboratory tests. These higher values he ascribes to the formation of corona on the ground and transmission wires. However, we assume the conservative value until Mr. Peek's more optimistic values have been established by further tests.

We have here an example of two methods of achieving results desired, both of which will increase the construction cost of the transmission line. However, the advantages of the ground wires

are not only due to the reduction of outages of a transmission line but are also due to the reduction of the surge potential and consequent reduction of hazard to apparatus connected to the line. If the first method is used it will be necessary to increase very substantially the insulation strength of the connected apparatus such as transformers, circuit breakers, transformer bushings, outlet bushings, etc., and, also, it would lead to an increased cost in the protective apparatus at the substation. However, a compromise can be made with the over-insulation method by using over-insulation only in the portions of the line exposed to lightning, using the lesser insulation at the unexposed points, but the reduction in outages will not be so great as if the extra insulation is used over the whole line or if ground wires are installed over the whole line. Another modification of these schemes might contemplate using extra insulation and ground wires in combination. For example, extra insulation might be used on portions of the line where grounding conditions aren't very good and ground wires may be used over other portions of the line where ground conditions are favorable and additional ground wires might be used in the neighborhood of the substation.

It will now be apparent that the insulation of the line, which includes so-called protective measures, is an economic problem, the problem of obtaining the lowest outage factor at the lowest cost. The two fundamental principles are the protective principle, such as the use of ground wires, and the principle of over-insulation. These two fundamental ideas can be combined in many different ways so as to obtain the best results. In the final result the effect on the substation apparatus such as transformers, circuit breakers, bushings, etc., must be considered. There are several other methods that are under consideration but have not reached the stage of development where they can be considered as being established. One of these methods is the use of arresters placed at intervals along the line. There is no doubt that if an effective arrester could be placed at each tower the result would be effective. Another method is known as the fused arcing ring. The economy and effectiveness of this method seems to rest almost entirely on the characteristic of the fuse. All these various methods can be considered properly as methods of effectively insulating the transmission line.



EFFECT OF GROUND WIRES

FIG. 4

There has been considerable controversy as to the advantage of using wood-pole construction and preserving the insulating characteristic of the wood pole itself. This of course comes under the heading of over-insulation. A great disadvantage of this method lies in the fact that the surges that are encountered in transmission lines are easily able to shatter, and from all accounts have frequently shattered the wood pole, leading to power outages due to mechanical failure. A modification of this method of obtaining improved insulation is the use of the insulated ground wire in conjunction with the wood pole. This has the advantage of preserving the wood-pole insulation and reducing the surge potentials to which the wood is exposed, thereby preventing a tendency to pole shattering. In the laboratory without lightning generator we are able to shatter wood poles of considerable length. It is easily seen, therefore, how much of a liability this pole shattering is in wood-pole construction where the line is exposed to lightning surge potentials and energies very much in excess of those that can be obtained in the laboratory.

Experience has shown that with certain types of line construction and degrees of insulation certain classes of transformer insulation are satisfactory and give good service. It seems to the writer that the method of classifying required insulation of connected apparatus by the number of units used in the adjacent insulator string is not only a good practical method of specifying the required class of insulation but is also scientific. In the future, the effect of the line construction on connected apparatus will be given more consideration and no doubt the use of special protective measures, such as additional ground wires near the substation, will grow in favor as more and more experience is obtained. The Westinghouse Company is carrying on investigations on lightning with the klydonograph, and expects to do further work with a modification of the Dufour oscillograph. It is hoped that, during the coming lightning season, by the above work in the field supplemented by the work being carried on in the laboratory with the lightning generator, we will materially add to our knowledge of lightning phenomena, thereby enabling us more intelligently to insulate our transmission lines against the effect of lightning, reducing outages due to this source.

J. F. Peters: I am heartily in favor of coordination of insulation but I am not so heartily in favor of the exact method suggested by Mr. Sporn.

In order that the insulation may be coordinated it will have to be done on a basis that is practical and not too expensive.

Insulation that goes into high-voltage apparatus, such as circuit breakers and transformers, is quite variable in its insulation strength; therefore, in establishing a chain of gradations this variation must be taken into consideration.

Referring to Chain 5 in Mr. Sporn's Table VII, you would have a line that must stand an impulse of 757 kv. but must fail at less than 834 kv. The bushings of the transformers must stand 834 kv. but must fail at less than 910 kv. The transformer windings must stand 910 kv. but must fail at less than 985 kv.

Now, the range between the values that insulation must stand and those at which it must fail are not large enough for practical application. It is one thing to design apparatus to withstand a certain voltage but it is an entirely different matter to design apparatus to fail at a point slightly higher than a specified value. By increasing those increments to a practicable value I am quite sure the strongest link in the chain will be so expensive that it cannot possibly be justified.

One way of getting around this difficulty that appeals to me as practical is to establish one point in the chain that is definitely weaker than the other links. That weak link logically should be either the line insulation adjacent to the station or some relief gap located adjacent to the station. When such a relief is fixed it would then only be necessary to say that all of the apparatus and substation insulation should be stronger than so much and in specifying this strength I heartily agree with Mr. Montsinger's suggestion of putting it in terms of 60-cycle dry flashover.

In connection with Mr. Lewis' paper, I have had occasion in the last few years to look over quite a few records of surge investigations on actual transmission systems and I have observed that there appear to be two kinds of impulses, one that comes under Class A as listed by Mr. Lewis in Fig. 3, the other as Class C in the same figure, and between these two types there seems to be quite a wide band. I do not have sufficient

information to state why this wide band exists but I am inclined to believe that the Class A are due to direct line hits and Class C are due to induced strokes. Now if this is the case, can we draw the conclusions that ground wires will have the same effect on reducing Class A disturbances as they will for Class C? All of the theories concerning ground wires are based on induced strokes and cannot apply to the direct strokes in the same way. There is no doubt that the presence of ground wires will divert many of the direct strokes and in that way will materially protect the line against such disturbances. But will they divert all of the direct strokes? If not, then the installation of ground wires will not produce lightning-proof lines.

F. W. Peek: It is significant that in these papers and in the discussion, lightning is expressed in numerical values; it is on an engineering basis. It is now known that the maximum lightning voltage that can appear on a transmission line depends upon the height of the line above ground and whether or not a ground wire is used. The maximum voltage that reaches the station and the apparatus is the lightning breakdown voltage of the line or the lightning arc-over voltage of the insulators. Since the voltage to which the apparatus is subjected is thus determined by the line insulators it is readily seen that it is not logical to use apparatus with a lower lightning breakdown voltage than the line insulators in the vicinity of the station.

An examination of statistics shows that a very small fraction of 1 per cent of transformers is damaged each year by lightning. Thus present transformer insulation is fairly well matched with present average line insulation. It would thus not be economical to add greatly to transformer insulation as long as the present average line insulation is used. However, as better service is demanded it is necessary to over-insulate lines in parts of the country where lightning is severe. If this over-insulation is carried up to the station the transformer strength should be increased in proportion to the increase in the insulation on the line. In many cases it will probably be found that satisfactory operation will be obtained with average insulation in the vicinity of the station and with any desired over-insulation out on the line. The lower insulation near the station on a comparatively short section would usually not appreciably increase the outages. This follows because the chance of an arc-over on a short section is small and further because high lightning voltages are rapidly reduced by corona and other losses before traveling a very great distance on the line. I am quite in sympathy therefore with the suggestions for balanced insulation on lines and apparatus as suggested in the papers by Mr. Lewis and Mr. Sporn.

Mr. Lewis has tabulated the average number of line insulators for various operating voltages and suggests that if the line insulation is increased above the average the transformer insulation should be also increased proportionally. He suggests that this increase be measured by the usual 60-cycle test of the transformer and that the line insulators be expressed not in terms of the number of units used but rather in terms of the 60-cycle arc-over voltage of the insulators. This is quite rational and removes a number of difficulties as to the lightning wave shape used, etc. It so happens that if a line insulator will protect a given transformer by flashover for a given lightning wave it will also protect it for other lightning waves. All this means is that over a wide range of transients the ratio between the lightning breakdown voltage of the insulator and of the transformer remains more or less constant. This follows because the insulator is a time gap or requires time to cause arc-over. It thus automatically takes care of changes in wave shape.

Another advantage of the insulator as a practical means of measuring the lightning voltage of transformers is that the operating engineer knows immediately whether or not the number of insulators on his line is stronger than the transformer.

I do not mean, of course, in endorsing Mr. Lewis' suggestion of using insulators as a measure of lightning strength of transformers that the actual lightning strength for various wave shapes should not be measured in the laboratory. In fact, we have done this very thing.

The following tests are given as illustrations and have particular bearing on the present discussion. Transformers were set up in the laboratory and connected to a transmission line supported by the usual line insulators. Lightning waves from the 3,500,000-volt lightning generator were sent over the line and the strength of the transformers measured in terms of insulator disks as well as voltage. These tests have been made with a number of different types of waves. I am particularly interested in this discussion because in 1915 I presented a paper before the Institute—*The Effect of Transient Voltages on Dielectrics*—covering this subject. In that paper the term "impulse ratio" was first used, as well as the term "micro-second" as applied to time lag and insulation breakdown. In this early work it was not possible to take oscillographs. However, this is now being done in the laboratory and studies have been made on insulator flashovers and insulation strengths with waves varying in length from 1/25 micro-second to several hundred micro-seconds.

By full use of available knowledge, it appears that transmission lines can be made almost or practically lightning proof.

K. K. Palueff: To illustrate the great variation in lightning characteristics of existing transmission systems I prepared, some three years ago, a table given below and quoted in part by Mr. Lewis.

Rated voltages	66	88	100	110	120	132	220
Total circuit miles......	4880	717	1617	2895	468	882	1150
No. of suspension insulators—...............							
Minimum...........	4	5	5	6	8	9	
Maximum..........	6	7	8	9	9	0	
Average............	5	6	6.4	7.23	8.83	9.7	13.
Height of lowest conductor at the tower—.....							
Minimum...........	22	28	34	25	30	42	
Maximum..........	53	47	55	68	61	55	
Average............	35	38.5	38.7	47	57	46.7	55.6
Percentage of total mileage that data are given on—...............							
Number of insulators.	100	78	100	100	100	100	52
Number of conductors	75	100	86	83	100	100	52

Since this table was prepared, the writer has learned of a 66-kv. system having 9 disks on entire line, of a 110-kv. system having 10 disks on entire line, and 15 disks at the substation end, of 132-kv. system having in addition to 9 disks 7.5 ft. wooden crossarms.

It also was found that a great many systems, having a more or less normal number of disks, were using wooden poles and crossarms with ungrounded hardware, which in some cases more than doubled the actual dielectric strength of the line.

Since Mr. Peek's laboratory investigation showed that lightning voltages on transmission lines may often exceed their dielectric strength, it became obvious that line insulation should be used as a measuring stick of dielectric strength of varius apparatus connected to it.

However, study of the line insulation data given above indicates that if such a principle is accepted then transformers and circuit breakers on some systems must be capable of withstanding high-potential test equal to far more than twice line operating voltage. For instance, a transformer for a 66-kv. system, with 9 disks as mentioned above, would require a high-potential test of four times normal (264 kv.). This of course means a substantial increase in cost of the apparatus.

The experience of some operating companies has proved the correctness of this principle, and forced them to buy transformers capable of standing a high-potential test of more than twice operating line voltage for their "over-insulated" lines.

The second group, however, were inclined to attribute the cause of their operating troubles to defectiveness of the apparatus, which attitude deprived them of an opportunity to benefit by their experience.

The third class of engineers, being annoyed by arc-overs of the bushing on circuit breakers and transformers, realized that the dielectric strength of their apparatus was lower than that of the lines, but instead of following the example of the first group they established a habit of securing extra strong bushings matching with line insulation, leaving, however, the apparatus proper at the original strength, thus virtually making the most expensive part of the transmission system the weakest.

It is on account of the above consideration that I most heartily welcome the recommendation of Mr. Sporn's paper.

The important question is how to ascertain the lightning strength of the apparatus. Making an impulse test as part of the acceptance test is at present quite out of the question, for two reasons: first, the range of shapes, and the magnitude of characteristic traveling waves met with in service are not sufficiently well established; second, there is no way of determining the place and degree of partial damage that may be done by such a test to a transformer. It is quite possible to puncture insulation between adjacent turns or even coils, with so little energy concentrated at the point of failure that it would be absolutely impossible to find the latter even after complete disassembly of the transformer.

Transformers respond to impulse, not as a pure inductance, but as a very complicated network of distributed capacitances and inductances. The result of it is that high-frequency voltage may concentrate between adjacent turns or coils.

This phenomenon is excellently described in Messrs. L. F. Blume and A. Boyajian's paper on *Abnormal Voltage within Transformer Windings*, (TRANS. A. I. E. E., Vol. XXXVIII, Part I, 1919, p. 577).

Thus two transformers, equally strong at low frequency (not greatly in excess of 500 cycles), may have quite different lightning strength. In spite of that, however, it seems that the only practical method of making acceptance tests is to subject apparatus to a sine-wave voltage of low frequency (say between 25 and 500 cycles). The value of low-frequency arc-over of the line insulation (which must include wooden cross-arms in case hardware is not grounded) of the system under consideration should serve as a criterion for the magnitude of potential test of the transformer.

J. F. Peters: I should like to add a few comments to what Mr. Palueff has stated so as to prevent any possible misunderstanding of the discussion. He gave a very beautiful analytical discussion that applies to an abrupt application of voltage to a transformer winding. His conclusions are what would happen if there were no other factors present except the capacitance and inductance of the windings; but what actually happens in service is quite different. All high-voltage apparatus are equipped with bushings that have high enough capacitance to alter very considerably the internal state of affairs. With a typical high-voltage transformer, if an impulse with a sheer front is applied, the capacitance of the bushings will absorb this impulse to such an extent that it will increase gradually to its full value in something like five microseconds. That being the case, the voltage is applied to the windings slowly enough that it distributes quite uniformly throughout the winding.

C. D. Gibbs: (communicated after adjournment) The papers by Mr. Lewis and by Mr. Sporn represent the first serious consideration given to coordinating the insulation of transmission lines with that of equipment. It is a feature that most engineers have encountered, but which, due to lack of data, has largely been settled by guess.

One point which I wish to bring out is that the problem has been started on the premise that the lines must be insulated to prevent flashover during lightning storms. This premise is justified only on some of the higher capacity lines such as the 220-kv. trunk lines where an interruption involves a loss of a large block of generating capacity. On the usual transmission line a circuit can be dropped out of service without upsetting the operation of the system and in these cases there is no justification for the expenditure necessary to make the line lightning-proof.

Too much effort is being made to secure higher and higher flashovers for transmission lines. By the use of wood poles, arms, and braces, the flashover may be doubled but the use of the overhead ground wire reduces the potential which will cause flashover by 50 per cent, so the number of interruptions remains the same in each case. In the former, the terminal equipment will be subject to much greater stresses. The additional cost of the extra insulation at terminals and on the lines must be very carefully weighed against the value of the loss of a line. After the terminal equipment is already established, the line insulation should be such that it does not endanger the equipment. That is, the problem is reversed. Instead of the line insulation being fixed and the transformer insulation determined from it, the transformer insulation is fixed and the line insulation should be coordinated with it.

Mr. Lewis recommends flat spacing of conductors. Such a recommendation is not based on the economics of the case. It has been determined that for a given width of right-of-way, 50 per cent more power can be transmitted at 132 kv. than at 220 kv., by using the conventional two-circuit tower for the 132-kv. line. This value may be further increased by using a three-circuit tower having the conductors in the vertical plane.

Another recommendation is that the flashover of the last one-half mile of line be lower than the rest of the line and additional ground wires installed. It is not apparent why this last one-half mile should be designed to function as an arrester. To do this, additional tower designs will have to be made resulting in an increase in the number of types used on the line with consequent increase in cost. Towers and insulators are very poor arresters. They may be satisfactory in relieving the overvoltage but every flashover is attended by an interruption.

It appears that the arresters should be called upon to perform the functions which Mr. Lewis assigns to the insulators of the last one-half mile of line. If the arresters are of insufficient discharge capacity they should be designed larger. Larger choke coils may be of distinct advantage or the installation of arresters on the bus. In any case, the arresters should not be rendered useless by permitting flashovers that will drop the line out of service when it can be avoided without additional cost.

C. A. Jordan: (communicated after adjournment) Despite the general tone of optimism which pervades Mr. Lewis' paper, lightning flashovers have occurred, and probably will continue to occur, on the most strongly insulated lines in service today. Probably a greater percentage of high surges measured on transmission systems by surge-voltage recorders arise from direct strokes to line structures or conductors than is now generally realized. Especially for lines of moderate voltages, it is not to be expected that any amount of insulation or ground-wire protection, within practical limits, will prove effective against these.

By increasing insulation levels of important transmission circuits and installing additional ground wires, much may be done to increase immunity to the average run of severe induced surges; hardly, I believe, as much as Mr. Lewis anticipates, however. For some unexplained reason, the operating history of transmission circuits with ground wires, engineered in accordance with the best modern thought, has fallen short of the bogey set by Mr. Lewis' data. For the past two or three years, numerous and earnest efforts have been made to measure with klydonographs the shielding effect of ground wires on operating circuits, without finding voltage reductions of the order indicated in this paper. In fact, to my knowledge, no reliable records of any considerable reduction have been obtained to date. As the theory of the ground wire is generally understood, it must remain substan-

tially at ground potential to exercise any appreciable shielding effect. Quite apparently, due to impedance in the ground wire and its earth connections, and possibly due to other factors of which we now have no knowledge, field conditions depart materially from laboratory conditions, even in the best of circumstances.

Since flashovers initiated by lightning cannot in the nature of things be avoided, it becomes necessary to exercise such control as is possible over the locations of these flashovers. It is not always easy to incorporate this control as a basic feature of design with confidence. The great difficulty is an almost utter ignorance of the surge impulse strengths, under various conditions, of the insulations commonly employed by the industry. I make this statement advisedly, having some slight knowledge of the research work which some manufacturers and operating companies have been, and are, conducting. Rational design will not be possible until the voltage-time characteristics and rates of fatigue of the common insulations, individually and in the combinations usually employed, have been determined, and the range of surge characteristics to be met with in practise has been established. The application of the cathode ray oscillograph bids fair to supply much of the latter information within the next few years. Laboratories equipped with surge generators should not lag in developing technique and determining the equally important insulation characteristics.

Only lightning discharges within a very limited area surrounding the yard can affect the substation directly. Thus the maximum fundamental value of most surges which can appear in the yard will be governed by the surge flashover voltage (which is variable within wide limits) of the insulators at the line entrance. If the yard and particularly the bus insulators are weaker than the entrance insulators for any surge condition, there is risk of yard flashover causing a station shutdown. If a flashover occurs on the oil circuit breaker bushings, there is usually the same risk. If a surge of dangerous magnitude penetrates the yard still further to the transformers before finding a point of relief, there is possibility of transformer failure. Obviously it is preferable to avoid yard flashover entirely, if possible.

It is because of the present lack of data upon which to base intelligent design, and the gradual realization of what must be done to improve the situation, that the self-protecting transformer has, of recent years, received serious consideration as a forward step in system design. The self-protecting transformer is one in which the internal insulation, taken as a whole, is able to support any potential which can pass the bushing. Granted, bushing failure is undesirable, but as between bushing failure and transformer failure, the former is the lesser of the two evils.

Mr. Lewis now proposes that the insulation strength of transformers to surge potentials be gaged in terms of the 60-cycle flashover voltage of the insulators used on the lines for at least one-half mile immediately adjacent to the station, and suggests limiting values of line insulation for the nominal system voltages 66 kv. and above. I do not believe this proposal, if generally adopted, will best promote the interests of the art. Aside from the obvious advantage of relieving the manufacturer from the development of improved methods of testing with a possible saving in production costs, no other advantage is, for the moment, apparent. On the other hand, the proposal has several serious disadvantages and even dangers.

The relative strengths of insulations vary materially with wave shape. Too little is at present known regarding distribution of surge stress throughout yards and apparatus in general, and transformers in particular, to feel any degree of confidence that all will be well if insulation strengths are graded for 60-cycles alone. Mr. Palueff in his discussion has analyzed this situation very well as regards the transformer.

The restriction of line insulation in a zone a half mile or more around a station has the serious operating disadvantage that it increases the likelihood of unnecessary line interruptions, even though ground wires be used, because advantage cannot be taken of surge attenuation in this zone. Such an extensive arrangement of "impulse spillways" does not seem necessary. A number of operating companies is using one set of protective gaps at the line entrance or elsewhere in their yards with satisfactory performance in limiting the magnitude of surges passing a point.

Modern high-voltage switchyards are usually quite extensive. A line entrance may be 1000 or more feet distant from a transformer bank. Limitation of line insulation at point of entrance would be of little benefit to the distant transformer bank. It is true that such a case is special and protective gaps or lightning arresters should be installed adjacent to transformers, the line insulation no longer being the governing factor. But the point is that a high percentage of installations *would* be special and the proposal to reduce insulation adjacent to the station could not be applied universally, even if it were desired to do so.

The greatest danger to progress would be a tendency, as a path of least resistance, to perpetuate the expression of one thing in terms of something entirely different, and related to it only in a very general and variable way. A sound eventual solution cannot be expected in that manner. The only cure is continued investigation and research. It will cost the industry effort and money, but I believe the expenditure will be more than justified.

W. W. Lewis: Referring to Mr. Peters' statement as to the effect of the capacitance of a high-voltage bushing in modifying an impulse which may reach the bushing from a transmission line:

I do not believe that a high-voltage bushing will have very much effect in this respect. This is apparent from the following consideration: An overhead transmission line has a capacitance to ground of the order of 0.010 μ f. per mi. The capacitance of a power transformer from high-voltage terminal to ground is of the order of 0.002 μ f. and a high-voltage bushing has a capacitance to ground of the order of 0.0002 μ f. Thus it will be seen that the capacitance of the transformer itself is 10 times that of the bushing and the latter has a capacitance that is equivalent to only 1/50th of a mile of line. In addition, the station busbars have an appreciable capacitance to ground, in some cases equal to or greater than that of the transformers.

Neither the transformer nor bushing capacitance would have any appreciable effect on a wave of very long duration. A short wave or a wave that had been chopped off by the line insulators would be affected slightly by the combined capacitance of the busbars, transformers, and bushings. The greater effect, however, would be due to the capacitance of the busbars and transformers. The bushings would have an insignificant effect, as they only add a few per cent to the station capacitance.

In considering these matters, we should take account not only of the most favorable cases, but also of the most severe cases. In these cases, we will not be able to lean very heavily on the station capacitance, which is too low to give much protection.

Philip Sporn: (communicated after adjournment) I was frankly very much disappointed and surprised at the stand taken by Messrs. Montsinger, Lloyd, Peek, and Peters in regard to the question of actually measuring impulse voltage. They stated it would be better to specify impulse strength in terms of insulators. Disregarding the point that Mr. Peek himself made, that it isn't until you begin to express data or relationships in actual numerical quantitites that you can claim that you are even beginning to talk in a scientific manner, I think there are numerous objections to expressing impulse strength in terms of insulators.

For one thing—and I believe this is the principal objection—there is great danger that by adopting that practise we will only continue the situation that we are confronted with now, which is admittedly bad. The operating people now find that they had been lulled into a false sense of security: they bought

equipment that was apparently good for certain voltage and sat back satisfied but later found it was breaking down, and it wasn't breaking down at the voltages for which they bought it but at other voltages. If the equipment is able to stand up for those other voltages they might as well know what magnitude it can stand up to and then they can use their judgment in determining how much of a factor of safety they ought to have.

Another objection to the proposed method of measurement is the fact that when we do express insulation strength in terms of insulators it might get us in trouble under a situation where a wave below the flashover value, say of the bushing of the transformer, comes in and is reflected at the transformer itself.

There is still a further objection, particularly on low voltage where wood lines are used. That is, if you talk of transformers or other apparatus as being good for a certain number of insulators, there is danger it will be taken at its face value, and we are going to have the difficulty that we are confronted with today and which Mr. Palueff brought out, and that is that you might have five insulators on a wooden line but the equivalent insulation strength might be actually 12.

It seems to me several of these difficulties could be eliminated if we started to express these values as actual numbers.

The objection has been raised that we haven't a standard. Well, that is only another good argument for establishing one. Standards have been established with regard to other quantities and can be with regard to this.

I don't think that anybody is particularly anxious to get insulation values down to a point where they will be expressed in such values that the accuracy will be good to plus or minus one per cent, but even though we don't go to such precision it will be still better, I think, to express them in actual numbers.

I think Mr. Fortescue has brought out the fact that the impulse flashover on a wave where the peak isn't reached in less than a microsecond is the power frequency flashover value. That may be so. I don't think there is any agreement on that, and it only brings out a point I have made, that we are still groping blindly and will continue to do so until we get some actual oscillographs on a number of systems, on many systems, and get hundred of oscillograms and find out exactly what lightning is and what its limits are, and so forth.

Mr. Peters has stated that he believes that the conditions today are very good and that, in general, transformers are standing up well, and apparently there is really no reason for disturbing them. I find it difficult to agree with that point of view. You don't have to have ten per cent of your transformers or of your other equipment failing to be in real trouble. For a particular station which may be one out of fifty stations on a system, a failure once a year or once every five years is a very serious matter, and it may cause considerable damage.

Neither do I agree with Mr. Peters in his statement that, if the strengths that were proposed in Table VIII were spaced by a practical amount instead of roughly the ten per cent as was suggested, the link of highest installation would reach so high a value that it would be entirely impractical. I know that in our own company we have now for a period of eleven years on one particularly extensive system been buying transformers considerably over-insulated; in fact, the standard specified has been a three times normal test instead of twice normal—the present A. I. E. E. Standard. Quite regularly, generally once a year, we survey the results of previous years to see whether we want to continue the same policy for the following year or two, and so far we have found it a paying proposition to continue it. I know, too, that we found it necessary to go up to higher insulations than the Institute Standards on some of our other voltages, and I believe there is quite a number of other operating companies doing, or starting to do, the same thing today.

I do not think that the question of rationalizing insulation strength is a particularly easy one, and I certainly did not want to convey the impression that it is. But suppose it isn't. There is a lot of work to be done on it. But if you examine Figs. 1 and 4 in the paper, Fig. 1 showing the present status with regard to insulation and Fig. 4 the proposed arrangement and presumably the status that will exist if the idea with modifications is carried through, I think that there is a good chance that the conclusion will be that all the trouble that may be necessary to bring about the conditions shown on Fig. 4 will have been worth while.

High-Speed Recorder

BY C. I. HALL[1]

Fellow, A. I. E. E.

Synopsis.—This paper describes a new electrical instrument for automatically recording variations of electrical functions at high speed. The rate of chart motion is lower than that of the oscillograph so that the envelope of an a-c. wave is produced. This recorder has been successfully applied in the analysis of breakdowns on transmission lines, giving data used as the basis of securing improved selective relay protection and for other problems involving automatic high-speed recording.

INTRODUCTION

THE rapid adoption of interconnection and the formation of complex power networks have made it increasingly difficult to provide adequate relay protection for these systems. The location and settings of selective relays must be such that overloaded or faulty lines are promptly isolated and cut off with a minimum of interference to the service continuity of the remainer of the system. The high-speed recorder is an instrument which has been designed particularly as an aid in the solution of these problems. It has been built in a variety of forms having either one or more recording elements and giving either maximum values only, or records having a time base. It is started automatically by the excessive current incident to the fault and begins to record in approximately 0.03 sec. In its four-element form, it gives simultaneous records of the neutral ground current and each phase-voltage, for a period of 10 sec. after the occurrence of the fault. This covers the life of the disturbance, since the faulty section is usually cut off in a few seconds by the protective relays.

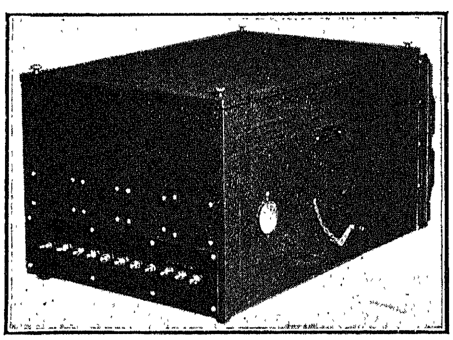


FIG. 1—GENERAL VIEW OF FOUR-ELEMENT RECORDER

Although the high-speed recorder was designed primarily as an aid in the study of line faults, it is obvious that it has numerous other applications, some of which are mentioned later. The recorder may be used in nearly any application in which automatic starting or high-speed recording are necessary.

The use of the recorder in analyzing transmission line faults has been described by E. M. Tingley in a paper entitled *The Hall High-Speed Recorder.*[2] Included in this paper were numerous records made in service on the system of the Commonwealth Edison Company. The purpose of the present paper is to deal particularly with the design and construction of the recorder, including sufficient test records to illustrate the varied application of the instrument.

REQUIREMENTS OF RECORDER

The design of the recorder incorporates the following features, which are considered essential to a device of this class:

a. Automatic Operation: Recording is started by a high-speed relay actuated by increase in line current or other determining variable.

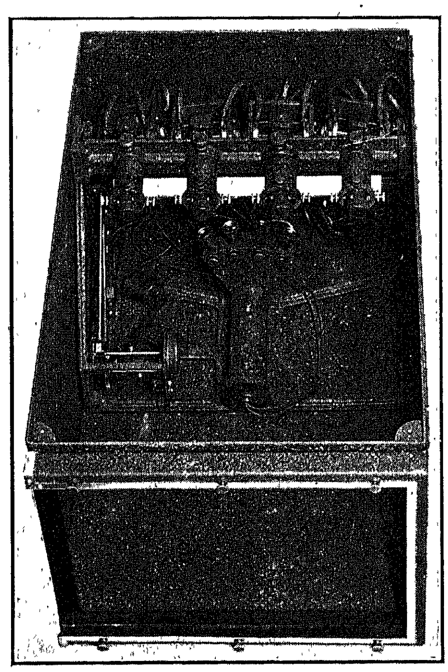


FIG. 2—INTERIOR OF FOUR-ELEMENT RECORDER

b. Speed of Recording: The record shows values for each half cycle on 25- and 60-cycle circuits.

c. Minimum Delay Before Beginning to Record: The total time after occurrence of the fault until the device begins to record is approximately 0.03 sec. It is

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Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

2. *The Hall High-Speed Recorder,* E. M. Tingley, 1928 QUARTERLY TRANS., No. 2, Vol. 47, p. 252.

obvious that this lag must be short in order that no part of the record be lost.

d. Sturdy Construction: Comparable to portable ammeters and voltmeters. The instrument contains no delicate parts which are likely to become damaged with ordinary handling and care.

e. Portability: The recorder may be easily moved about from place to place, and set up in condition for recording.

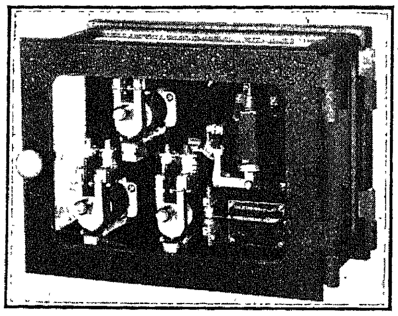

FIG. 3—AUXILIARY RELAY FOR FOUR-ELEMENT RECORDER

f. Improved Light Source: The light source is more effective and efficient than types used heretofore. An intensely brilliant point of light is produced on the recording film, yet the input is low, so that dry cells can be used as a power source.

g. Daylight Loading: Standard photographic film holders are used, enabling loading and unloading in daylight as with an ordinary camera.

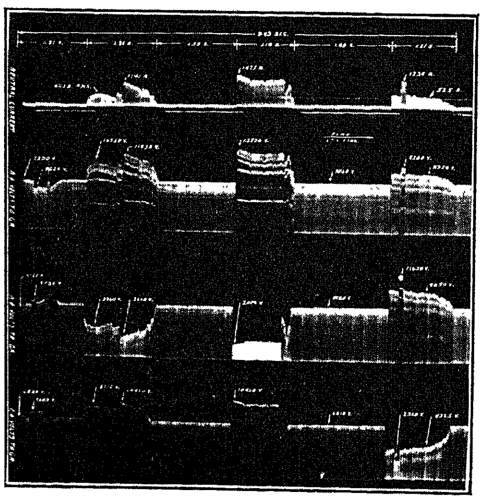

FIG. 4—RECORD MADE BY FOUR-ELEMENT RECORDER ON SYSTEM OF COMMONWEALTH EDISON COMPANY

CLASSES OF RECORDERS

As previously mentioned, the recorder has been produced in both four-element and single-element form. Views of the former device are shown in Figs. 1 and 2 while the latter is shown in Figs. 7 and 8.

Fig. 4 shows a chart obtained from a four-element recorder in service on the lines of the Commonwealth Edison Co. The upper record of this chart gives the variation in neutral ground current while the three lower records give voltage values on the three phases. Ordinates represent current and voltage values, and time movement is from left to right.

Fig. 10 gives a group of four calibration records made with a single-element recorder of the stationary film type. With this construction, maximum values only are recorded. The single-element recorder has been arranged also to give time-base records by the application of the moving film mechanism shown in Fig. 9. The latter is contained in a light-tight case which is attached to the top of the recorder proper, taking the place of the ordinary film holder shown in Fig. 7.

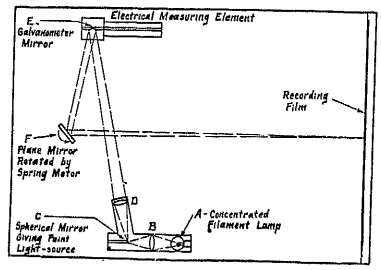

FIG. 5—SCHEMATIC DIAGRAM OF LIGHT SOURCE AND OPTICAL SYSTEM, FOUR-ELEMENT RECORDER. (SIDE VIEW)

LIGHT SOURCE

A side view of the four-element recorder drawn schematically is shown in Fig. 5. This cut also illustrates the type of light source used in all recorders. A small concentrated filament automobile type lamp, A, is placed in one end of a light-tight tube which also contains lenses B and D and a highly polished metallic hemispherical mirror C. The rays from the lamp are focused upon the hemispherical mirror, which, through reflected light, becomes a secondary light source of very small diameter and high intensity. The rays from this secondary source pass through lens D to the galvanometer mirror E, from which they are reflected to plane mirror F and thence are focused upon the record-

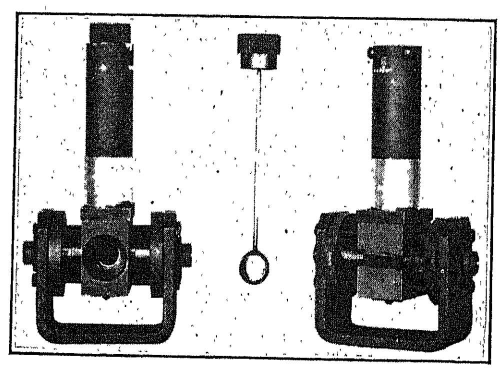

FIG. 6—ELECTRICAL MEASURING ELEMENT. FRONT AND REAR VIEWS AND VANE ONLY

ing film. During the time of recording, the plane mirror F is rotated at a definite rate in the direction indicated by the arrow by a governor-controlled spring motor. This rotation of mirror F causes the recording point of light to move across the stationary film at the rate of 1 in. per sec. Only one lamp and secondary source are required for all four recording elements, as four lenses D, located in an arc of a circle above C and transmit-

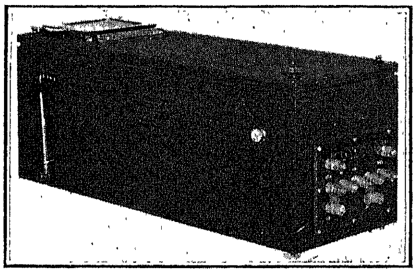

Fig. 7—General View of Single-Element Recorder

ting light to four individual galvanometer mirrors are used. This will be understood by referring to Fig. 2.

Electrical Element

A detailed view of a recording element is shown in Fig. 6. This element consists of a soft iron yoke supporting two adjustable poles which carry the

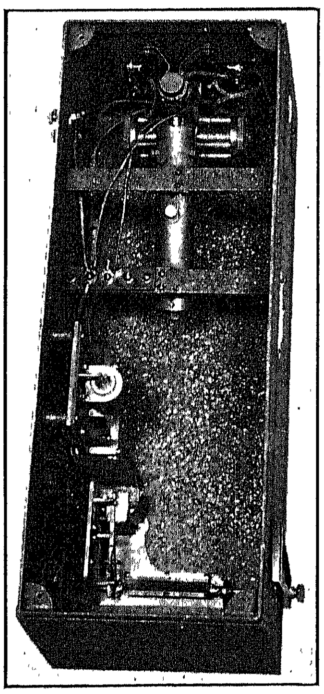

Fig. 8—Interior of Single-Element Recorder

winding. The moving element is a soft iron vane, mounted rigidly on the end of a stiff duralumin rod and set at an angle of 45 deg. to the flux path between the poles. An aluminum support riveted to the vane carries a galvanometer mirror and a guide bearing pivot. The vane and mirror assembly is shown between the front and rear views of the complete element. For use on a-c. circuits the electrical elements are connected to the lines through transformers contained within the recorder. In this way, proper ratings are obtained and a standard element can be used for recording either current or voltage. When d-c. circuits are being studied, the transformers are replaced by special external shunts.

The moving system or vane is of low inertia and high

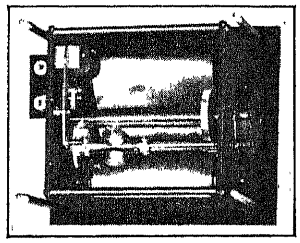

Fig. 9—Moving Film Mechanism for Single-Element Recorder

period of oscillation, so that it readily follows changes during each half cycle. In contradistinction to the usual indicating or recording element of standard instruments having a fine hair spring for furnishing the restraining torque, the elements of the high-speed recorder use the torsional force in the stiff duralumin rod mentioned above, to return the element to its zero position. The use of this relatively stiff moving system

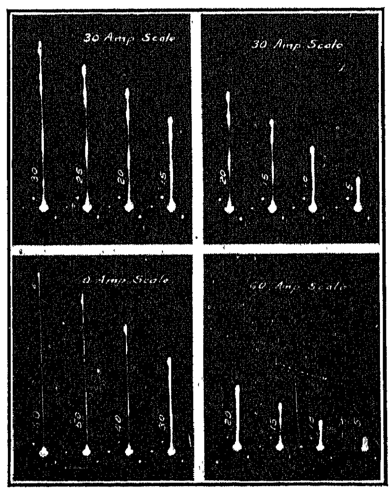

Fig. 10—Calibration Records Made With Single-Element Recorder

results in a very reliable element which is not liable to damage in shipment or handling. The light beams and photographic film used in recording also eliminate the inertia inherent in other methods of recording.

Operation

As indicated earlier, the high-speed recorder begins operation automatically upon the occurrence of an overload, or fault. This is accomplished through a high-speed current-operated relay which is continuously connected in the neutral ground circuit. The high-speed relay for the four-element recorder is contained in a separate case (Fig. 3) while that for the single-element device is contained inside the case of the recorder proper.

In operating, the high-speed relay energizes three small contactors which connect the voltage elements to the line. The high-speed relay also turns on the recording lamp and releases a constant speed spring motor which rotates the plane mirror F of the four-element recorder or advances the film in the single-element recorder. At the end of the recording period a contact is opened by the spring motor which completely deenergizes the recorder control circuit, turning off the light source and disconnecting the recording elements. The operator, upon arrival, renews the film, rewinds the spring motor, and releases a latch in the high-speed relay. The recorder is then ready for operation again, and the exposed film is taken into a dark room for development.

Records

The size of record furnished by the four-element recorder is 11 in. by 14-in., and is made on standard film. The records made by the single-element recorder, stationary film type, are 3¼ in. by 4¼ in. and are also made on standard film. The single-element recorder for moving film uses standard 3¼ in. by 5½ in., 12-exposure Kodak film.

Scales

Standard deflection scales are as follows:

a. Four-element device
70 volts per in.
5 amperes per in.

b. Single element (ammeter)
On 30 ampere coil —10 amperes per in.
On 60 ampere coil*—20 amperes per in.

Time Lag of Relay and Lamp

It is important that the time required for the high-speed relay to operate and for the lamp filament to reach recording brilliancy be very short, in order that the record may cover the complete disturbance. Tests have shown these time lags to be as follows:

*Note. The ammeter coil of the single-element recorder is equipped with taps so that if desired, only one-half of the winding may be used, thus doubling the current capacity of the instrument.

a. Lag of High-Speed Relay on 60 Cycles

Per cent of critical current	Time in sec.	Cycles at 60 ~
150	0.0058	0.348
200	0.0035	0.210
500	0.0020	0.120
1000	0.0012	0.072
2000	0.0010	0.060

b. Lag of Recording Lamp

Lamp rating	Volts applied	Time in sec. for lamp to begin to record	Cycles at 60 ~
18-24 v., 27 cp. auto headlight.	35.5	0.027	1.62

c. Total Time to Begin to Record
(Sum of lags of high-speed relay and lamp)

Per cent of critical current	Time in sec.	Cycles at 60 ~
150	0.033	1.97
200	0.031	1.83
500	0.029	1.74
1000	0.028	1.69
2000	0.028	1.68

Miscellaneous Applications

The possible applications of this type of instrument are numerous and varied. Figs. 11 and 12 show test

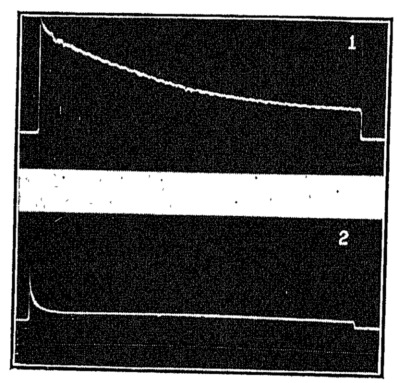

Fig. 11

1. 20-Ampere load applied to 1-kw., 150 volt, d-c. motor-generator set.
2. Starting current of 200-watt Mazda C lamp.

records made using slight modifications of the standard recorder in order to give a time scale of 5 in. per sec. and also to add a timing indication to the chart. The latter was done by focusing the rays of a small high-speed filament hydrogen-filled lamp on the lower edge of the film. This lamp was operated by a 60-cycle supply circuit and thus produced on the record a row of timing dots 1/120 sec. apart.

Chart 1, Fig. 11 shows the variation in current following the application of a 20-ampere load to a 150-volt d-c. line supplied by a small 1-kw. motor-generator set. The record shows how the current rose at once to a maximum value and then tapered down gradually, owing to a reduction in speed of the overloaded motor-generator. The detail of the record is exemplified by the small variations in the record line

caused by sparking of brushes. The timing dots show that the complete interval during which the circuit was closed was 1.2 sec.

Chart 2, Fig. 11 shows the starting current of a 200-watt Mazda C lamp, indicating the initial rush of current with cold filament and the reduction in value as the filament becomes heated.

Fig. 12 shows the blowing of plug and cartridge fuses under various conditions on a 220-volt d-c. circuit. In each chart, ordinates represent current values and time reads from left to right. Chart 1 was made by a 6-ampere plug fuse connected in series with a 20-ampere resistance load. The fuse blew in approximately 0.75 sec. and the arc was extinguished quickly. Chart 2 was made by another plug fuse of

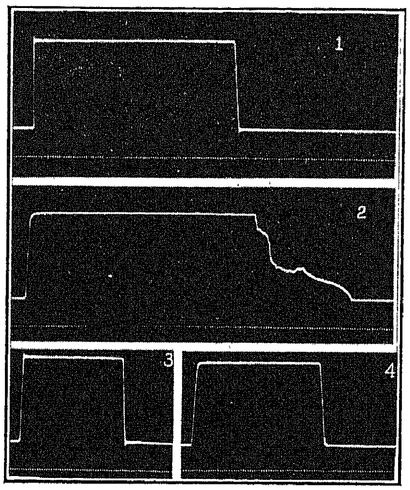

FIG. 12—BLOWING OF FUSES ON 220-VOLT D-C. CIRCUIT

1. 6-Ampere plug fuse on 20-ampere resistance load
2. Same as "1" except inductive load
3. 5-Ampere cartridge fuse on 20-ampere resistance load
4. Same as "3" except inductive load

the same rating and with the same current value, but using an inductive rather than a resistance load. It will be noted that in this case the current value builds up more gradually and that an arc continues for about 0.35 sec. after the fuse wire has melted.

Chart 3, Fig. 12 shows the blowing of a 5-ampere cartridge fuse on a 20-ampere resistance load. Chart 4 shows the same conditions except for the substitution of an inductive load. It will be noted that the cartridge fuse opened the inductive current without the formation of an arc.

Other suggested uses for the high-speed recorder include the investigation of starting currents of motors, motor current values on high overloads of short duration, brief reductions in line voltage due to starting of motors or other high-current loads, and general laboratory investigations where the device may be used for visual readings or permanent records.

Discussion

HALL HIGH-SPEED RECORDER

(HALL)

PAGES FROM THE HALL HIGH-SPEED RECORDER[1]

(TINGLEY)

NEW HAVEN, CONN., MAY 9, 1928

Alexander Dovjikov: In an effort to overcome the slow response of ink-recording instruments, Mr. Hall devised the instrument described in his paper and in the paper by Mr. Tingley. This instrument is of the type intermediate between the ink-recorder and the oscillograph. By introducing the galvanometer and photographic method of recording, Mr. Hall eliminated to a certain degree the distorting features of the moving masses of the recorder although a small amount of overshooting may still be observed on the records.

The convenience of the Hall recorder in using the stationary plate instead of a rotating film as in the oscillograph is compensated by the fact that the former cannot record a second disturbance until the photographic plate is changed. Due to this limitation the instrument will require more attention and in certain cases the operation of the system, such as the reclosing of a breaker on a fault, cannot be recorded unless the time of a single operation of the recorder is unreasonably extended.

The statement of Mr. Tingley that "starting on neutral ground current is the best compromise that can be effected" may be true in application to Mr. Tingley's system for measuring of values he had in mind but is not generally true for all systems because this relay, functioning on ground current, will not operate in case of a phase-to-phase short circuit unless it develops into a fault to ground. We believe that a modified negative-sequence relay, which may be applied to grounded or ungrounded systems and will operate in the case of a ground fault as well as in the case of a phase-to-phase short, will be preferable in many cases.

C. I. Hall: Mr. Dovjikov mentions the moving masses of the recorder, as affecting the accuracy of the instrument. It should be understood that the recorder element has been so designed as to have a minimum of inertia and high restraining torque in the torsional rod carrying the vane. The angular twist of the recording vane is very small (about 1.2 deg. per in. of deflection on the film). In addition, the optical method of recording eliminates all inertia effects other than those originating in the galvanometer element. As the result of the foregoing features of design, overshooting of the recording element is small and is not sufficient to interfere with the commercial accuracy of the instrument.

The comment has also been made that the stationary film used in the recorder permits of recording only one disturbance without renewing the film. This is true of the four-element recorder only, as the single-element device is equipped with an automatic moving film mechanism which records four successive disturbances.

1. A. I. E. E. Quarterly TRANS., Vol. 47, No. 1, Jan. 1928, p. 252.

A High-Speed Graphic Voltmeter
for Recording Magnitude and Duration of System Disturbances

BY A. F. HAMDI[1] and H. D. BRALEY[1]
Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—*This paper deals with a graphic voltmeter for recording the magnitude and duration of system disturbances. It also deals with operating experiences with this device, together with the importance of the data obtained.*

INTRODUCTION

THE high-speed recording voltmeter described in this paper is one of a number of types now on the market which have been built in order to supply the needs for a type of instrument which would give an accurate record of system disturbances. It was felt that such instruments would be useful in determining actual magnitude and duration of disturbances and their relation to the operation of high-tension circuit breakers and relays on apparatus connected to the system.

The first part of this paper deals with the description of the electrical and mechanical details of this instrument, with particular reference to the requirements which were submitted to the manufacturers who developed the device. These requirements resulted from four years of operating experience with a similar type of instrument which accomplished the results desired. The second part of the paper deals with the interpretation of the records obtained and their value to the engineering and operating departments in analyzing system disturbances.

Several years ago the Engineering Department and Test Department of the New York Edison Company investigated the methods available for obtaining records of voltage dips during disturbances on power systems, and as a result an instrument was developed which consists of a high-grade graphic voltmeter driving a chart at normal speed and an auxiliary circular chart driven at relatively high speed. To the pen arm of the graphic voltmeter is attached a long pointer in addition to the standard pen of the instrument. This long pointer reaches over to a circular smoked chart which revolves at the rate of 2.5 rev. per min. (24 sec. per revolution). This circular chart is driven by a d-c. motor operating from the station control battery so that its speed is not influenced by the changes in system voltage. With this device it is possible to obtain records of both magnitude and duration of all disturbances. Two of these instruments have been in successful operation for four years and have given quite satisfactory results. The main objection to this device is that the smoked chart has to be renewed after each disturbance. It was therefore desired to obtain an instrument which would eliminate the above difficulty by giving the high-speed record on the standard strip chart.

From the operating experience obtained with the above instruments, certain specifications were drawn which were placed in the hands of instrument manufacturers and resulted in the development of the instrument described in this paper. With this device the high chart speed is 3600 times the normal chart speed and the change-over is accomplished in 0.05 sec. or less (1 to 3 cycles for 60-cycle systems).

The following characteristics were required:

1. A graphic voltmeter responsive to all voltage fluctuations, but well damped so as to be free from over- or under-shooting even for 100 per cent voltage fluctuations (suddenly energized to 115 volts or 115 volts suddenly interrupted).

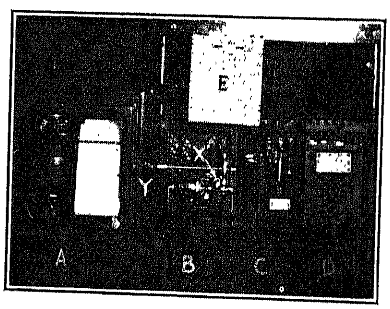

FIG. 1—GENERAL VIEW OF A GRAPHIC SYSTEM—DISTURBANCE RECORDER

2. Instrument to take 1.0 sec. or less to reach 115 volts when suddenly energized.
3. High-speed timing accuracy to be within 0.1 sec.
4. Chart acceleration time 3 cycles or less on 60-cycle systems (0.05 sec.).
5. Low-voltage relay capable of being set to function on a voltage dip of 5 per cent of normal or less.

The manufacturers were left entirely free to work out all details.

DESCRIPTION

The device described in this paper is illustrated in Fig. 1. It consists primarily of a standard type of graphic voltmeter *A*, a chart accelerator *B*, a contact-making voltmeter *C*, and the necessary resistors *D* and *E*. The wiring diagram of this device, together with

1. Assistant Engineer, The New York Edison Company, New York, N. Y.

Presented at the Regional Meeting of the A. I. E. E., Northeastern Dist. No. 1, New Haven, Conn., May 9-12, 1928.

the schematic layout of the component parts, are shown in Fig. 2.

All the component parts of the above device are designed to operate at 115 volts, 60 cycles, with the exception of the magnetic clutch, which operates at 120 volts d-c. The contact-making voltmeter can be set to function at all dips in voltage amounting to two per cent of normal, or more. Actually, however, it is set to function at 5 per cent dips.

Under normal operating conditions the strip chart of

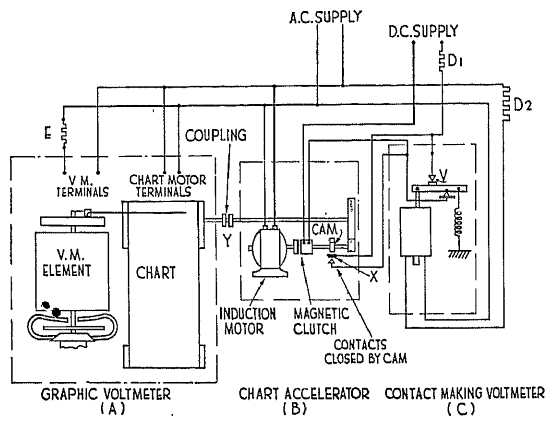

FIG. 2—SCHEMATIC LAYOUT AND WIRING DIAGRAM

the graphic voltmeter A runs at the normal speed of 3 in. per hr.; the salient-pole induction motor of the accelerator B runs continuously at synchronous speed; and the contact-making voltmeter C being energized at full voltage holds open its contact V. As soon as a dip in voltage occurs, amounting to five per cent of normal or more, the contact-making voltmeter closes its contact and energizes the magnetic clutch of the chart accelerator B. When the clutch engages, the chart accelerator motor runs the strip chart of the graphic

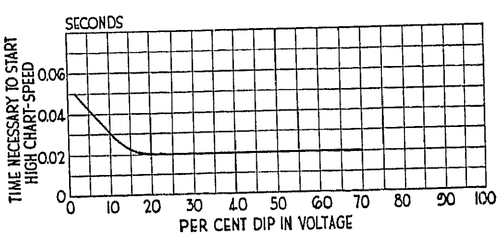

FIG. 3—STARTING TIME OF HIGH CHART SPEED

voltmeter at the high speed of 3 in. per sec. The high speed continues even after the disturbance is over, for a length of chart equivalent to 24 hr., or 24 sec. in actual time. At the end of this time, a cam, which is operated by a worm gear, located on the magnetic clutch shaft, opens the circuit of the magnetic clutch at point X (see Figs. 1 and 2). If the voltage is back to normal, the slow chart speed is resumed as the contact-making voltmeter contact V would then be open. In case the voltage is still below normal, the contact-making voltmeter will have its contact V closed and the cam will keep the device running at high speed for an additional period of 24 sec. Normally the cam holds the contact at X open.

The time necessary for the accelerator to speed up the chart has been carefully investigated and was found to be dependent upon the magnitude of the voltage dips which affect the speed of operation of the contact-making voltmeter. For all dips amounting to more than 20 per cent of normal the device requires 0.02 sec., (1.2 cycles) to change over to the high speed. With dips less than 20 per cent, the change-over time may be as high as 0.05 sec. (3 cycles). The variation in this time is shown in Fig. 3.

The timing accuracy of the high-speed chart is correct within 0.1 sec. for the full length of the high speed run

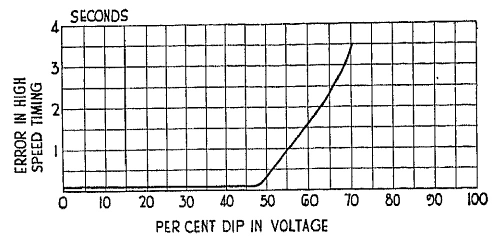

FIG. 4—TIMING ERROR IN 24 SEC. AT HIGH CHART SPEED

(72 in. length of chart) providing the dip does not exceed 50 per cent of normal. For greater dips in voltage, the accelerator motor slips and the timing error becomes greater. The curve in Fig. 4 shows the timing error during 24 sec. for voltage dips up to 70 per cent. For voltage dips beyond 70 per cent the driving motor stops if the disturbance is sustained. However, the motor requires about 5.5 sec. to come to rest even if the voltage fails completely. Fig. 5 shows the record of a 100 per cent dip lasting for 1.08 sec., where the magnitude was correctly recorded. The time was in error by 0.2 sec. It should be noted, however, that for 100 per cent dips lasting for more than one sec. the magnitude can be

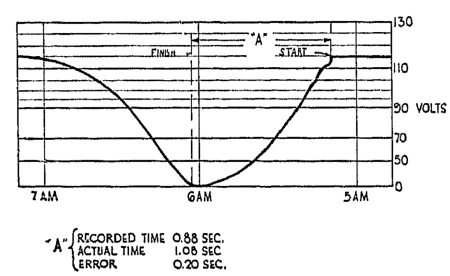

FIG. 5—TEST RECORD OF A COMPLETE VOLTAGE FAILURE

Voltage reestablished at the end of 1.08 sec.

obtained directly from the chart even though the duration is not correctly recorded.

To permit correct time resetting for slow speed after a disturbance, the high speed should last 24 sec., but actually it lasts only for about 23.96 sec. Therefore, there is a reset error in timing amounting to approximately 0.12 in. of chart length, which at slow speed means 2.5 min.

After the contact-making voltmeter operates to energize the magnetic clutch, 0.28 sec. is required for the cam to close the "hold-in" contact at X (see Fig. 2). Therefore, for disturbances having durations of less than 0.28 sec., the high speed lasts only as long as the disturbance, and the cam does not come into play. Fig. 6 shows such a short duration disturbance which was cleared in about 0.1 sec. However, if a number

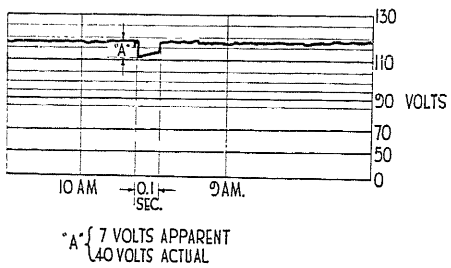

Fig. 6—Record of Momentary System Ground—Cause Unknown

of short disturbances occur in succession, the cam will close the contact at X and a length of chart equivalent to 24 hr. will be run off as soon as the several short duration disturbances add up to 0.28 sec.

In Fig. 7 is shown a set of calibration curves applying to this recorder. These curves have been prepared by

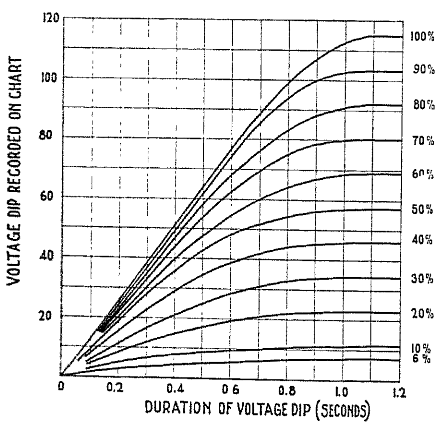

Fig. 7—Calibration Curves for Determining True Voltage Dip

subjecting the device to voltage dips of known magnitude and duration, and plotting voltage values obtained from the chart (ordinates) against time (abscissas). Normal voltage was 115 volts.

The following procedure would be used to obtain the magnitude of a disturbance of known duration. From the high-speed section of the chart, obtain the apparent maximum dip in voltage and the duration of the disturbance. Plot the point corresponding to these two observations on the calibration curves. The true per cent voltage dip can then be obtained by comparing the position of the point so plotted to the calibration curves. As an example, if the apparent voltage dip were 40 volts, and the duration of the disturbance were 0.40 sec., we find by reference to Fig. 7 that the point determined by these two values falls very close to the 60 per cent dip curve. Therefore, we conclude that the actual dip was approximately 60 per cent of normal or 70 volts.

In connection with these calibration curves it should be pointed out that it is quite essential to have a properly damped instrument. If the instrument overshoots to a considerable amount, the records will not be smooth curves as shown in Figs. 8, 9, and 10, but will be wavy curves. Reference to the calibration curves in Fig. 7 shows that in the case of the instrument

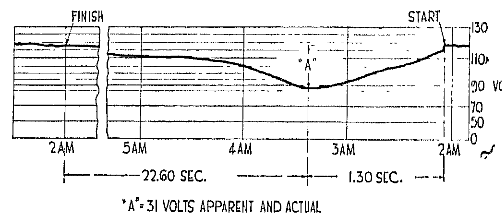

Fig. 8—Record of Short Circuit on 13,800-Volt Feeder

discussed, there is no overshooting and the instrument reaches full indication in about 1.1 sec. In other words, for disturbances lasting over 1.1 sec. there is no need for reference to the calibration curves, as the maximum dip recorded on the strip chart is the true dip.

Operating Experience

Since this instrument was placed in service, on a 60-cycle cable system, 15 records of voltage disturbances were obtained. Most of these voltage dips were 20

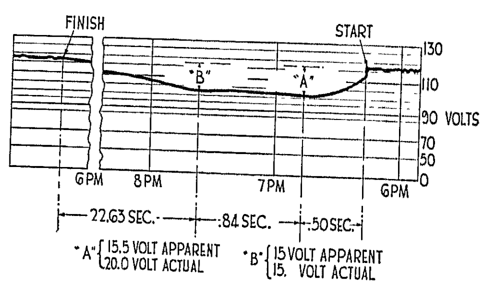

Fig. 9—Record of Short Circuit on 13,800-Volt Feeder

per cent or less of normal voltage and the trouble was cleared from the system automatically in 1.5 sec. or less. While practically all of these faults show the same characteristics, there were a few cases of rather different nature which illustrate the adaptability of the instrument for this service. In the following figures the smooth voltage recovery sections have been cut off in order to shorten the length of the records. The broken lines show where chart sections have been cut off.

Fig. 8 is a typical record which is representative of the voltage disturbances resulting from faults on the system. This record shows a dip of 31 volts, or approximately 26 per cent, the disturbance being cleared by the opening of the circuit breakers after 1.3 sec. It may be noted that the duration of the disturbance is measured from the start to a point where the voltage begins to recover.

Fig. 9 illustrates a disturbance which lasted for 1.34 sec. before it was finally cleared. The first circuit breaker opened after 0.50 sec., while after an additional 0.84 sec. the second circuit breaker cleared the other end of the feeder. Since the first switch opened after but 0.5 sec. the instrument did not attain its maximum swing, the calibration curves showing the actual dip to be 20 volts instead of 15.5 as recorded. This curve also illustrates the manner in which it is often possible to obtain a check on relay operations, as two distinct circuit breaker operations are indicated.

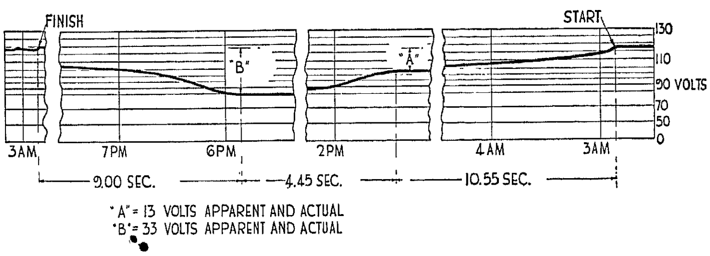

Fig. 10—Record of Ground and Short Circuit on 27,000-Volt Feeder

Fig. 10 is an unusual case in that the disturbance lasted for approximately 15 sec. before it was finally cleared. In this case a triplex cable became grounded at a considerable distance from the supply end and was not cleared immediately because the moderate ground current was insufficient to cause the overload relays to operate. The voltage dip due to the ground was approximately 11 per cent and lasted about 10.55 sec. Apparently the ground then developed into phase trouble causing a dip of about 28 per cent and was finally cleared after an additional 4.45 sec.

In each of the above cases the records show that a considerable length of time is required for the voltage to return to normal. Of this time, one sec. is due to time lag in the instrument if the dip is 100 per cent. If the dip is less than 100 per cent, the time lag of the instrument will be correspondingly reduced.

Fig. 6 illustrates a case in which a momentary ground occurred which apparently cleared itself in about 0.1 sec. The contact of the contact-making voltmeter opened before the cam could operate the hold-in contact to continue the high-speed operation.

While an instrument of this nature will not record instantaneous changes in voltage or current, it does afford a means of giving directly a fairly accurate picture of the disturbance even though it may last several minutes. All disturbances are recorded by this instrument even if they last more than 24 sec. because the instrument will operate continuously through successive periods of 24 sec. as long as the contact-making voltmeter contact is closed. An instrument designed to operate on current instead of voltage, for example, would give a record of surging between generating stations due to a condition of instability which might last for several minutes. Such an instrument may also be installed at grounding points to indicate the magnitude and duration of ground fault currents as a check on the effectiveness of the grounding itself and for checking relay operations.

The results obtained with the device described have been quite satisfactory from both the operating and the maintenance standpoints. The records obtained have given sufficiently accurate information in regard to the magnitude of voltage dips and their relation to operation of low-voltage relays. These records have an additional value in that they often afford a means of checking automatic circuit breaker operations and also give a fairly accurate indication of the effect of faults on the system in general.

Discussion

J. E. McCormack: (communicated after adjournment) We have had some experience with an instrument similar in construction to the one described by Messrs. Hamdi and Braley in their paper.

We have experienced considerable difficulty in maintaining an accurate calibration on this instrument. The graphic voltmeter is equipped with an oil dash pot to damp the meter and prevent overswinging on a dip. The calibration of the meter depends almost entirely on the amount and viscosity of the oil in the damping chamber, and changes in temperature, or evaporation or leakage of the oil, will throw the calibration off.

We have also found that the slip of the induction motor driving the high-speed device is sufficient to cause a discrepancy in time as high as fifteen or twenty minutes on each high-speed run. This discrepancy varies with the amount and duration of the dip in voltage.

In respect to the electrical location of the disturbance recorder in the station, we have found that the only satisfactory method of connection is on one phase of one feeder or bus section. An attempt was made to connect a recorder to six 13,200-volt feeders on two sections of a bus, but the voltage difference between the two sections was sufficient to keep the chart running continually at high speed. Any method of connection to one feeder or bus with automatic throw-over to the other when the first is taken out of service is inherently wrong since the throw-over switch causes an indication of a dip at every operation. Also, a heavy dip is likely to cause the throwover relay to operate and makes an analysis of the dip impossible.

D. J. Angus: (communicated after adjournment) The desirability of speeding up the chart of graphic meters when important records are to be obtained was recognized about fifteen years ago, when the company with which the writer is connected was called upon to furnish graphic recording pressure gages for use in air-brake testing. These gages were provided

with a pressure-controlled mechanism which speeded the chart up from three in. per hour to three in. per minute when any abnormal operation took place, and returned the speed to three in. per hour after this condition had passed.

Later, when public utilities felt the need for an instrument of this kind, it was found necessary to continue the rapid speed of the chart after the trouble ceased, until the chart came to the same time marking, 24 hours later on the chart, before resuming the slow chart speed, in order that a number of records could be secured in succession, without any attention on the part of the operator. Mr. Hamdi mentioned the cam-operated holding-in device, which requires approximately 0.28 seconds before it becomes operative. My experience has been that the holding-in device must operate the instant the high-speed drive comes into play, because if it does not, the circuit to which the tripping mechanism is connected may be disconnected by the automatic oil switches or other protective devices, and no high-speed records secured of the trouble and the recovery after the disturbance. Often this recovery will take several minutes, and a complete record of it is of utmost importance.

Instruments which the writer has designed for power-plant service are equipped with a double cam arrangement such that the first momentary impulse locks it in the high-speed position, where it remains until at least 24 hr. of chart (24 sec.) has been passed.

In the next to the last paragraph of Mr. Hamdi's paper, he mentions that an instrument designed to operate on current instead of voltage would give a record of surging between generating stations due to a condition of instability which might last for several minutes. We have actual records from large generating stations connected by tie lines operating out of synchronism for over four minutes, and numerous records where the system did not steady down to normal operation until after a minute had elapsed.

In addition to recording voltage and current in times of trouble, instruments equipped with the high-speed chart mechanism have for a number of years been used to record the power factor or phase position of the current in reference to the voltage in the generator leads and tie lines, the power transfer in kilowatts, kv-a. pressures surges in pipe line feeding hydraulic turbines, speed changes in prime movers, and pressure or other mechanical records of the functioning of governing equipment.

High-speed graphic recording instruments are long past the experimental stage, and hundreds of them are in use securing a wide variety of data on the operation of the various pieces of equipment that make up a modern power generating and distributing system.

A. F. Hamdi: Referring to Mr. McCormack's remarks, I should like to point out that we had predicted the difficulties he mentioned and that they have been eliminated in the device discussed in this paper by the use of a magnetically damped "dead-beat" voltmeter and a motor running at synchronous speed.

Referring to Mr. Angus' remarks, I should like to point out that with the device described, we obtain high-speed records of any and all disturbances. The fact that disturbances lasting less than 0.28 sec. do not result in a complete 24-hour run at high speed is of no particular importance, because usually such disturbances are of no serious consequence and they clear themselves as discussed in connection with Fig. 6 of the paper.

Particularly in view of the facts brought out by Mr. McCormack, I have to take exception to Mr. Angus' statement and hold the view that although hundreds of such devices are in use, they are still more or less in the experimental stage.

Selection of Motor Equipment by Principle of Similar Speed-Time Curves

BY BERNDT A. WIDELL, JR.[1]

Member, A. I. E. E.

Synopsis.—Data for making preliminary estimates of speed of cars required and capacity of motor to do a given service have been rather limited. The object of this paper is to show a method whereby it is possible to provide curves which are simple to calculate and easy to apply.

No mathematical formula has ever been derived to express the speed–time or current–time curves for a railway motor. Similarity between speed–time curves has been resorted to and this paper shows how this method can be used to give very accurate results by proper consideration of the various factors which influence the shape of the speed–time curve.

Previous methods for estimating motor capacities are based on the horsepower of motor required, but with the advent of the self-ventilated and blown motors it is necessary to calculate the r. m. s. current for a given cycle and select a motor having this continuous rating. A method for doing this is proposed, based on similar current–time curves.

The limiting values of average running speeds for given rates of acceleration and braking, and the data for obtaining motor capacity necessary at these limits are indicated on each curve. This helps one to visualize why it is not practicable to perform certain schedules on a fixed rate of acceleration and braking basis.

ONE of the most complicated engineering problems is that of selecting the proper motor equipment to perform a given railway service. By "service" we mean that cars must make a given number of stops and slowdowns over a route in a given time. In many instances the profile of the route is hilly, and voltage varies on different sections of the route, thus making it necessary to consider small sections of road at a time in our calculations to arrive at a suitable motor equipment. Unless one has had considerable experience in the application of motors to different services, it may require weeks of calculation to determine on the motor equipment of required speed to do the service with the least energy consumption and a conservative motor capacity. As a first approximation it is usually assumed that the route is absolutely level. An average line voltage is also assumed, thereby reducing the work to a few simple speed-time curves. In the majority of cases, such a solution is accurate enough, but if it is not, sufficient information has been obtained to shorten the work of making detailed calculations over the entire profile as it actually exists and for the varying line voltages. Even with this simplification, considerable calculation may be necessary before the proper speed equipment is determined, or it is found that an uneconomical or impossible schedule has been requested.

Several electric railway engineers (among them, E. H. Anderson, A. H. Armstrong, and F. W. Carter) have plotted curves from which a rough approximation of the speed of equipment necessary to do a certain service can be made. These curves have been prepared for a very limited group of conditions for which they give accurate data. They can also be used, however, as a rough approximation for other conditions, but realizing that much more accurate curves could be plotted to cover greater ground, an investigation was made which showed that the car friction and slope of the motor speed-tractive effort curve were the factors which most influenced the shape of the speed-time curve, and hence the schedule speed, for a given rate of braking and acceleration. Referring to Fig. 1, curves *B* and *C* are speed–time curves for a certain weight of car, making the same scheduled speed for the same length of run. The speed on leaving control and free running speed are shown in the table. It should be noted that for the same value of car friction there is a 5.5 per cent

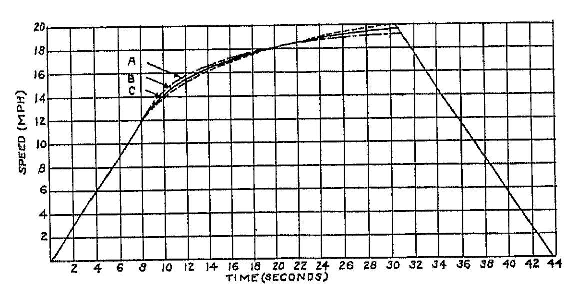

FIG. 1—SPEED—TIME CURVES ILLUSTRATING THE DIFFERENCES IN SHAPE DUE TO THE SLOPE OF SPEED TRACTIVE EFFORT CURVE AND THE CAR FRICTION

A—Average motor characteristic, friction 40 lb. per ton
B—Flat motor characteristic, friction 20 lb. per ton
C—Steep motor characteristic, friction 20 lb. per ton

Speed on leaving control (mi. per hr.)	A—12.9,	B—11.8,	C—11.2
Free running speed (mi. per hr.)	A—20.1,	B—22.3,	C—23.9

Conditions: Length of run 830 ft., rate of acceleration and braking 1.5 mi. per hr. per sec. Average running speed 12.96 mi. per hr. Constant car friction

difference between speeds on leaving control, and 7 per cent difference between free running speeds, due to different motor characteristics alone. Comparing curve *C* with *A*, the difference between speeds on leaving control and free running speeds is 15 per cent and 19 per cent respectively. Obviously, if we are to make up curves that are to possess any degree of accuracy, the car friction and slope of speed—tractive effort curve must be considered.

First let us consider the effect of the slope of motor

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characteristic on the schedule speed. In order to distinguish between two different motor characteristics, the one whose speed tractive effort curve has the greatest slope is termed steep, whereas that with the less slope is flat. Fig. 2 illustrates the difference in

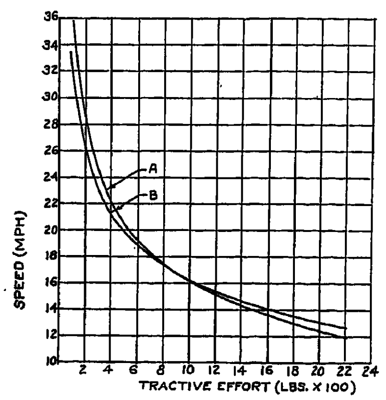

FIG. 2—SPEED—TRACTIVE EFFORT CURVE OF TWO MOTORS HAVING A DIFFERENCE IN SLOPE

A—Steep motor characteristic
B—Flat motor characteristic

the two motors' characteristics. Referring to Fig. 3 and assuming the number of stops per mile being made as one, we can read the free running speed corresponding to the average running speed directly. With an equipment geared to 75 mi. per hr., the following

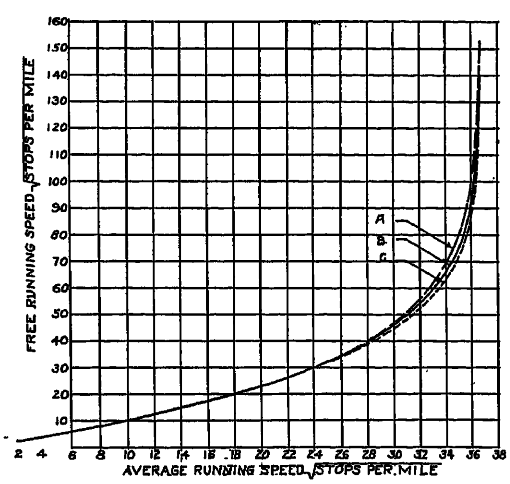

FIG. 3—CURVES ILLUSTRATING THE DIFFERENT FREE RUNNING SPEEDS REQUIRED FOR MOTORS HAVING DIFFERENT SLOPE SPEED—TRACTIVE EFFORT CURVES

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. Constant car friction 20 lb. per ton. No coasting, no leeway

A—Steep motor characteristic
B—Average motor characteristic
C—Flat motor characteristic

average running speeds can be made with a motor having the steepest and flattest characteristic respectively 34.6 mi. per hr. and 35.3 mi. per hr., a difference of 2 per cent. With a 35-mi. per hr. equipment, the difference in average running speed is 1 per cent, and with an equipment of 30 mi. per hr., an average running speed of 24 mi. per hr. is obtained with either slope of characteristic. Over the usable part of this curve, the maximum variation in average running speed due to the slope of motor characteristic is 2 per cent. If we base the curves on an average motor characteristic as indicated, the maximum variation in average running speed from either steep or flat characteristic is about 1.4 per cent.

Next let us consider the effect of car friction on the average running speed. Referring to Fig. 4, a series of curves has been plotted using an average motor characteristic as determined in the above paragraphs. With a 75-mi. per hr. equipment, the average running speeds that can be made with car friction of 10, 20, 30, and 40 lb. per ton are respectively 33.6, 35.0, 35.5, and 36.0 mi. per

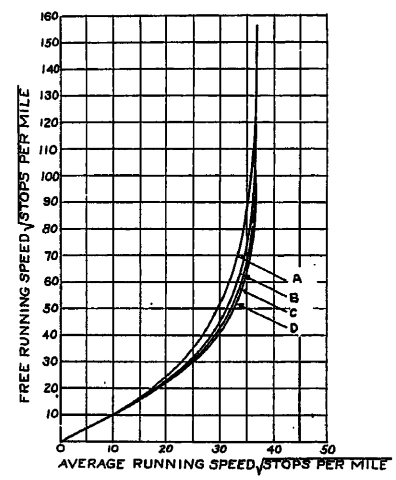

FIG. 4—CURVES ILLUSTRATING THE DIFFERENT FREE RUNNING SPEEDS REQUIRED WITH A MOTOR HAVING AN AVERAGE SLOPE SPEED—TRACTIVE EFFORT CURVE FOR VARIOUS CAR FRICTION VALUES

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at values given

A—10 lb. per ton car friction, B—20, C—30, D—40

Use: Abscissas are the values of average running speed times √ stops per mile, and corresponding values of ordinate on friction curve divided by the √ stops per mile gives the free running speeds necessary to make the average running speed

hr. The per cent differences in average running speeds are respectively 4.2, 1.5, and 1.3. Practically all other curves of a similar nature have been based on 20 lb. per ton friction; hence, the error where the actual friction is 10 lb. per ton is 4.2 per cent, for 30 lb. per ton friction 1.5 per cent, and for 40 lb. per ton friction 2.8 per cent. We can eliminate this error by using the average motor characteristic and plotting curves for the various friction values encountered, in which case the maximum error in average running speed calculated from these curves should not exceed 1.4 per cent.

The method by which curves of Fig. 3 and Fig. 4 were calculated is a development of the similar speed–time curve idea. For instance, if speed–time curves are calculated, using the average characteristic and a given rate of acceleration and braking for different

lengths of run, a series of different shaped speed–time curves is obtained. The shortest run will be represented by a triangle, a slightly longer run will show the car accelerating according to the slope of motor characteristic and value of car friction and the longest run will be practically at free running speed. If a means is obtained for expressing each of these speed–time curves in terms of similar speed–time curves to give

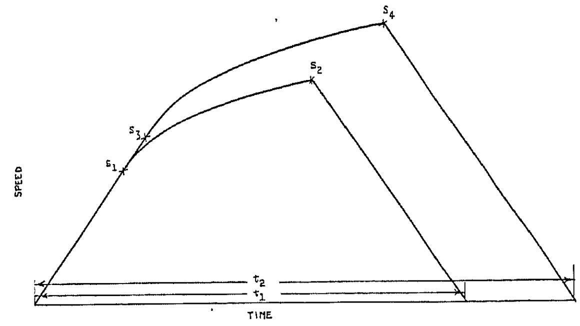

FIG. 5—SIMILAR SPEED—TIME CURVES

greater or less distance traversed, it will be possible to represent every existing running condition. How this is accomplished can be best explained by referring to Fig. 5.

Let D_1 = distance traveled in t_1 seconds.

D_2 = distance traveled in t_2 seconds.

On an assumption that the two curves are similar, the following relations are true.

$$\frac{D_1}{D_2} = \left(\frac{S_1}{S_3}\right)^2 = \left(\frac{t_1}{t_2}\right)^2 = \left(\frac{V_1}{V_2}\right)^2 = \left(\frac{S_2}{S_4}\right)^2$$

where $V_1 = \dfrac{D_1}{t_1}$ and $V_2 = \dfrac{D_2}{t_2}$ = average running speed

or since $D_1 = \dfrac{5280}{\text{stops per mile}_1}$ and $D_2 = \dfrac{5280}{\text{stops per mile}_2}$

we can write $\dfrac{\text{stops per mile}_2}{\text{stops per mile}_1} = \left(\dfrac{S_1}{S_3}\right)^2 = \left(\dfrac{t_1}{t_2}\right)^2$

$$= \left(\frac{V_1}{V_2}\right)^2 = \left(\frac{S_2}{S_4}\right)^2$$

And by transposition, using an abreviation of stop per mile S/M,

$$\underline{S/M_1}\ S_1^2 = \underline{S/M_2}\ S_3^2$$

or $$\sqrt{S/M_1}\ S_1 = \sqrt{S/M_2}\ S_3 \qquad (1)$$

and similarly $$\sqrt{S/M_1}\ V_1 = \sqrt{S/M_2}\ V_2 \qquad (2)$$

$$\sqrt{S/M_1}\ t_1 = \sqrt{S/M_2}\ t_2 \qquad (3)$$

$$\sqrt{S/M_1}\ S_2 = \sqrt{S/M_2}\ S_4 \qquad (4)$$

Referring back to the different shaped speed–time curves, we can calculate $\sqrt{S/M_1}\ S_1$ and $\sqrt{S/M_1}\ V_1$ for each speed–time curve and plot a curve of (average running speed) $\times \sqrt{\text{stops per mile}}$ against (speed on leaving control) $\times \sqrt{\text{stops per mile}}$. Equations (1) and (2). S_1 of Fig. 6 shows such a curve based on the average characteristic. The value of S_1 is the product of (speed on leaving control) $\times \sqrt{\text{stops per mile}}$. There is also shown a S_2 curve, the value of S_2 being (speed at which braking starts) $\times \sqrt{\text{stops per mile}}$. Equation (4).

Thus, knowing the schedule speed required and the

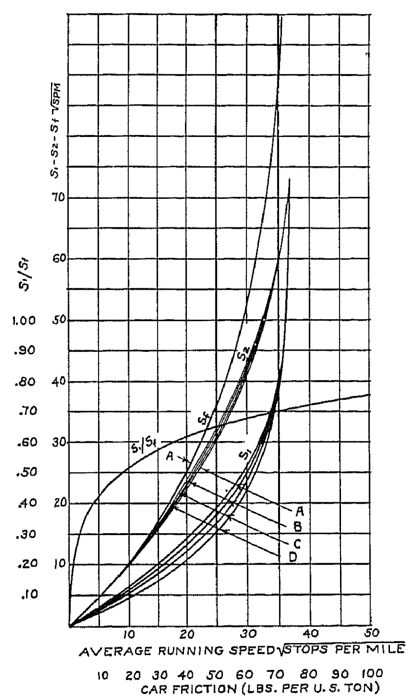

FIG. 6—CURVES FOR ESTIMATING SPEED AT END OF ACCELERATION, SPEED AT INSTANT OF BRAKING AND FREE RUNNING SPEED

S_1—Speed at end of acceleration times $\sqrt{\text{stops per mile}}$
S_1/S_f—Ratio of speed at end of acceleration to free running speed
S_2—Speed at which braking commences times $\sqrt{\text{stops per mile}}$
S_f—Free running speed times $\sqrt{\text{stops per mile}}$

A—10 lb. per ton car friction
B—20 lb. per ton car friction
C—30 lb. per ton car friction
D—40 lb. per ton car friction

Conditions: Rates of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at values given

Use: For a given value of abscissas; the free running speed is equal to value of ordinate S_1 divided by the value of ordinate S_1/S_f for proper car friction value and by $\sqrt{\text{stops per mile}}$, or to the value of ordinate S_f divided by the $\sqrt{\text{stops per mile}}$; the speed at instant of braking is the value of ordinate S_2 divided by the $\sqrt{\text{stops per mile}}$

average length of run, the speed on leaving control can be calculated from Fig. 6 and a motor selected with a gear ratio such that it will have this speed at the tractive effort necessary to accelerate the car at the desired rate and at the average line voltage. However, this curve (Fig. 6) is not applicable to the tapped field motor because the speed on leaving control resistance points is quite different for a tapped and full field motor when

both motors are geared to make the same free running speed. In view of the fact that a tapped field motor will make practically the same schedule speed as a full field motor, each having the same free running speed, and also to the fact that the free running speed of a full field motor can be expressed accurately in terms of the speed on leaving control, a more practicable set of curves has been calculated showing the relation between (average running speed) $\sqrt{\text{stops per mile}}$ and (free running speed) $\sqrt{\text{stops per mile}}$. From these curves the free running speed necessary to make a given schedule speed can be estimated using either a full or tapped field equipment.

The method of expressing the free running speed in terms of the speed on leaving control was suggested by Mr. E. E. Kimball's paper presented before the A. I. E. E. in 1908. Mr. Kimball noted that the tractive effort had a logarithmic relationship to speed and therefore knowing the speed at one value of tractive effort the speed could be calculated for any other value of tractive effort by the following equation.

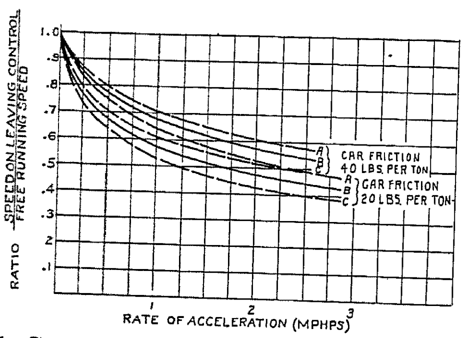

Fig. 7—Curves Illustrating Change in Ratio of Speed on Leaving Control to Free Running Speed with Various Values of Accelerating Rates, Car Friction, and Slope of Motor Speed Tractive Effort Curves

A—Flat motor characteristic
B—Average motor characteristic
C—Steep motor characteristic

Formula
$$\frac{S_1}{S_f} = \sqrt[A]{\frac{p}{P}}$$

Where S_f = Free running speed mi. per hr.
S_1 = Speed on leaving control mi. per hr.
A = Exponent expressing relationship between tractive effort and speed of motor characteristic
p = Car friction at free running speed (lb. per ton)
P = Tractive effort required to accelerate car at a given rate (lb. per ton)

$$S = S_0 \sqrt[3]{\frac{P_0}{P}} \qquad (5)$$

Where S = speed at tractive effort P
S_0 = speed at tractive effort P_0

The cube root factor in Equation (5) represents the slope of the speed—tractive effort curve and as stated by Mr. Kimball was selected because of the ease of making certain calculations. The variation in this slope factor was determined by plotting speed against tractive effort on logarithmic paper for several motors varying in capacity. In the majority of cases the resultant curves were perfectly straight throughout the range of voltage and current that the motors would be normally used. Therefore, the logarithmic relationship between speed and tractive effort can be expressed by the following equation.

$$T\,E \times S^a = K \qquad (6)$$

where $T\,E$ = tractive effort (lb.)
S = speed mi. per hr.
a = exponent determined from plot (slope factor)
K = constant determined from plot

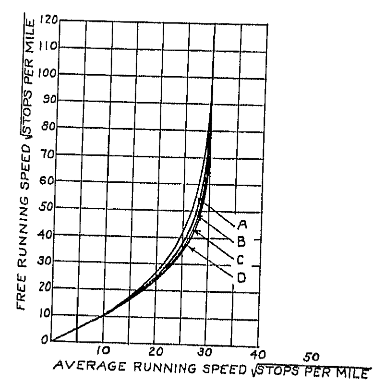

Fig. 8—Curves for Estimating Free Running Speeds

Conditions: Rate of acceleration and braking 1.0 mi. per hr. per sec. No coasting, no leeway, car friction constant for values given

Use: Abscissas are the values of average running speed times $\sqrt{\text{stops per mile}}$ and corresponding values of ordinate on friction curve divided by the $\sqrt{\text{stops per mile}}$ gives the free running speed necessary to make the average running speed

A—10 lb. per ton friction, B—20, C—30, D—40

The values of (a) varied between 2.8 and 3.5 representing, respectively, the steepest and flattest motor characteristics. A motor charcteristic having a slope factor of 3.2 represents the average slope of all motors considered and is that used as a basis of these curves.

Equation (5) shows that the ratio of speed on leaving control to free running speed depends on the slope of speed tractive effort curve, the car friction, and the rate of acceleration. Fig. 7 shows the variation of this ratio according to Equation (5). It is evident that with a given set of conditions the free running speed is a simple ratio of the speed on leaving control.

A set of curves based on different rates of acceleration and braking encountered in normal train operation, of (average running speed) $\sqrt{\text{stops per mile}}$ against (free running speed) $\sqrt{\text{stops per mile}}$ gives a ready means for determining the rates of acceleration and braking required and the free running speed necessary with those rates to make a given average running speed. Figs. 4, 8, and 9 show the character of such curves covering normal street car conditions.

As an illustrative example, suppose it is required to make a 37.5 mi. per hr. average running speed over average runs one mile long. By inspection of curves

such speed cannot be made with 1 or 1.5 mi. per hr. per sec. accelerating and braking rates but with a 2.0 mi. per hr. per sec. rate of acceleration and braking a free running speed of 64 mi. per hr. per sec. is necessary assuming car friction at 20 lb. per ton. With this speed equipment it would be impossible to maintain an average running speed of 37.5 mi. per hr. over the usual roads due to traffic conditions and the fact that some

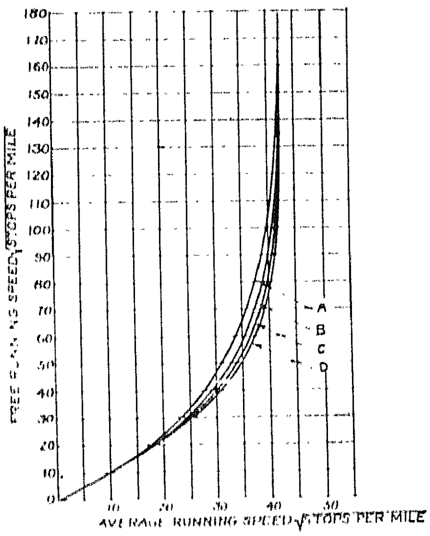

Fig. 9 Curves for Estimating Free Running Speeds

Conditions: Rate of acceleration and braking 2.0 mi. per hr. per sec. No coasting, no leeway, car friction constant for values given

A 10 lb. per ton car friction, B 20, C 30, D 40

Use: Abscissas are the values of average running speed times √ stops per mile and corresponding values of ordinate on friction curve divided by the √ stops per mile gives the free running speed necessary to make the average running speed

coasting must occur. We shall, therefore, assume that an equipment to give a 5 per cent faster average running speed will take care of these delays. Our equipment must then be able to make 39.4 mi. per hr. average running speed when pushed to the limit and have a free running speed of 73 mi. per hr., according to Fig. 9, assuming car friction has increased to 25 lb. per ton.

The curves as plotted were calculated on the assumption of a constant value of car friction from start to stop and are therefore only strictly accurate in the case where a car ascends a grade with no car friction. It is possible to plot the curves of free running speeds, r. m. s. current, and energy consumption using variable friction, but to do this involves the necessity of selecting an average friction curve. An examination of the many curves on car friction reveals not only a wide variation in friction values for the same car construction and weight, but also the ratio of car friction at end of accelerating period to that at the free running speed varies approximately as follows.

Single motor cars	0.55 to 0.40
Multiple unit cars	0.75 to 0.65

It is questionable, therefore, whether a single set of curves based on some average conditions of variable car friction would enable more accurate estimates to be made than using flat friction values.

The curves as calculated for constant friction values give results on the side of safety regarding free running speed, r. m. s. current, and energy consumption, if the actual car friction at free running speed is used. If values of r. m. s. current per ton and energy consumption are estimated on basis of car friction for speed at instant of braking, which is found from Fig. 4 curve S_2, a very close estimate of these values can be had.

By a similar manner in which the free running speeds have been obtained, the r. m. s. current can be estimated. Referring to Fig. 10, a series of curves gives the values of A corresponding to the (average running speed) times $\sqrt{\text{stops per mile}}$. This factor is the actual value of (r. m. s. current per ton) times

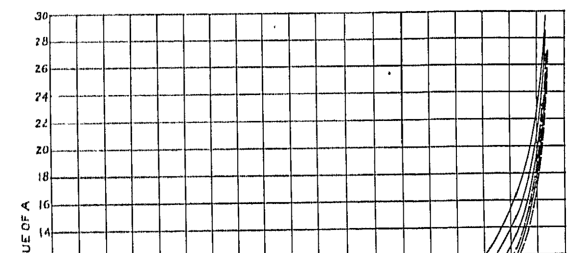

Fig. 10—Curves for Estimating Root-Mean-Square Currents for Specified Number of Stops per Mile and Schedule Speed

———— Full field motor
- - - - - - - - Motor operating with 100 per cent & 60 per cent field

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway

Use: Obtain value of ordinate A on curve of car friction corresponding to average running speed √ stops per mile and apply in following formula

$$\text{R. m. s. current} = \sqrt{\left[\frac{\text{Value of } A}{\sqrt{\text{stops per mile}}} \times T \times \frac{600}{V}\right]^2 \left[\frac{t_1}{t_1\, t_s}\right]}$$

Where T = tons per motor
V = average line voltage
t_1 = time to make run excluding duration of stop (sec.)
t_s = duration of stop (sec.)

A—40 lb. per ton friction
B—30 lb. per ton friction
C—20 lb. per ton friction
D—10 lb. per ton friction

$\sqrt{\text{stops per mile}}$. The value r. m. s. current per motor as determined from curves must be either increased or decreased according to the average line voltage in question according to its variation from 600 volts on which the curves are based. The actual continuous rating of motor required is decreased from that estimated from curves when considering the duration of stop by the following relation.

$$I_1 = \sqrt{I_0^2 \left(\frac{t_1}{t_1 + t_s} \right)} \qquad (7)$$

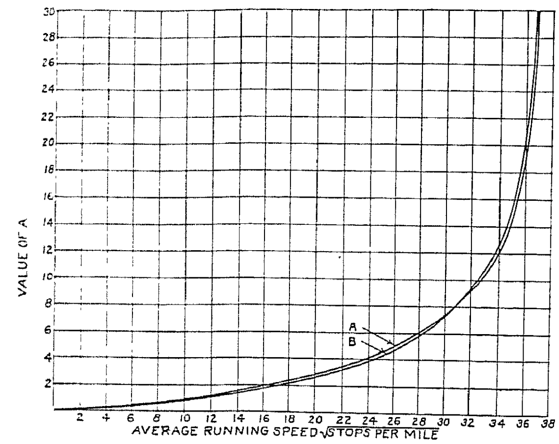

FIG. 11—COMPARISON OF ROOT-MEAN-SQUARE CURRENT FOR SPECIFIED NUMBER OF STOPS PER MILE AND SCHEDULE SPEED WITH MOTORS OF DIFFERENT SPEED—TRACTIVE EFFORT CHARACTERISTICS

A—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{3.52}}$

B—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{2.88}}$

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at 20 lb. per ton

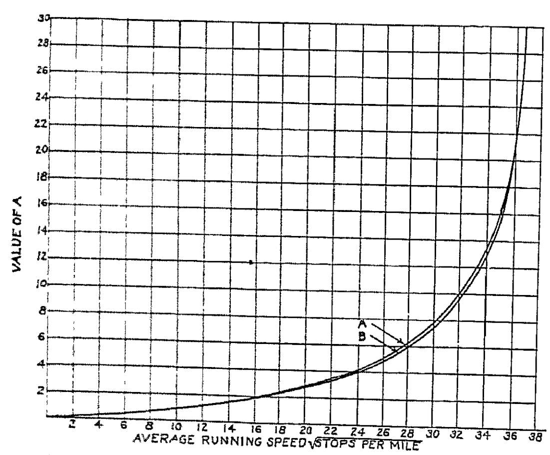

FIG. 12—COMPARISON OF ROOT-MEAN-SQUARE CURRENT FOR SPECIFIED NUMBER OF STOPS PER MILE AND SCHEDULE SPEED WITH MOTORS OF DIFFERENT SPEED—TRACTIVE EFFORT CHARACTERISTICS

A—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{3.33}}$

B—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{2.79}}$

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at 20 lbs. per ton

Where I_1 = r. m. s. current including time of stop

I_0 = r. m. s. current excluding time of stop (value obtained from curves)

t_1 = time to make run excluding stop (sec.)

t_s = duration of stop (sec.)

An interesting comparison of the current required for a steep and flat motor characteristic can be made as shown on Figs. 11 and 12. This first curve is based on two motors having considerable differences in efficiency and shows that the steep characteristic motor demands less continuous capacity to perform a given schedule up to 30.9 than the motor with flat characteristic, but for greater values than 30.9 the condition reverses. Fig. 12 shows two motors having practically the same efficiency and favors the steep motor characteristic.

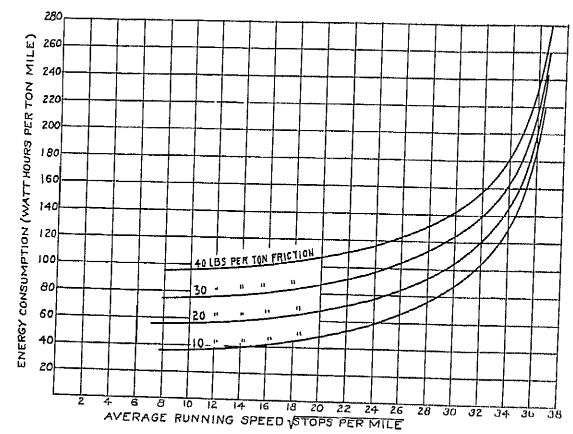

FIG. 13—CURVES FOR ESTIMATING ENERGY CONSUMPTION

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant for values given

Use: Read energy consumption direct from proper friction curve corresponding to the average running speed √ stops per mile

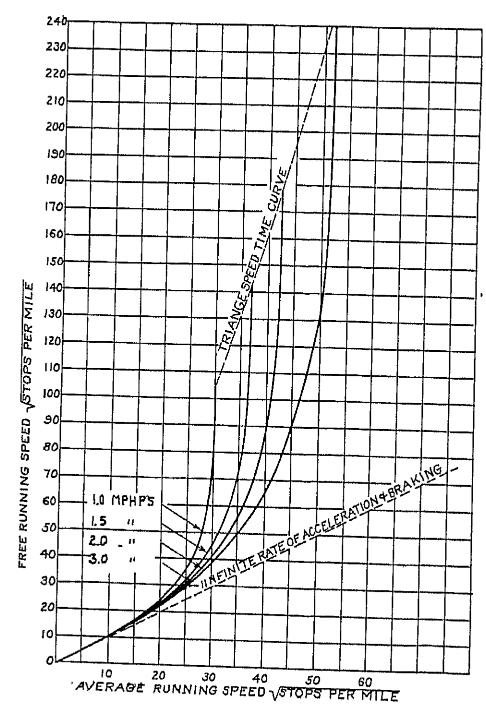

FIG. 14—CURVES FOR ESTIMATING THE INCREASE IN AVERAGE RUNNING SPEED WITH A GIVEN FREE RUNNING SPEED FOR DIFFERENT RATES OF ACCELERATION AND BRAKING

Conditions: No coasting, no leeway, car friction constant at 20 lb. per ton

The curves of energy consumption on Fig. 13 are useful in determining the maximum energy consumption for a given schedule but as in case of the curves on r. m. s. currents they will not give accurate estimates unless a prediction can be made of the efficiency of the motor that will perform the service required.

The importance of making the best possible approximation of car friction is apparent on inspection of Figs. 10 and 13 for curves of r. m. s. currents and energy consumption, respectively. For example, assuming runs of one mile average length and an average running speed of 30 mi. per hr. the r. m. s. current per ton according to Fig. 10 is 7.4 for car friction of 20 lb. per ton and 6.3 for friction of 10 lb. per ton; a difference of 17.5 per cent. The energy consumption under same conditions is 105 watthour per ton mile for 20 lb. per ton car friction and 88 watthour per ton mile for 10 lb. per ton car friction; a difference of 19.2 per cent.

The greatest differences in average running speeds are those due to changes in the rates of acceleration and braking for cars having the same free running speeds. Fig. 14 shows these differences for rates between 1 and 3 mi. per hour per sec. It would appear from these curves that the highest rates would be the most advantageous, but we are limited to following considerations: first, comfort to passengers; second, in city service where high rates are desirable motors must be of light weight with small wheel diameters. This precludes use of large gear reduction or slow-speed motors with the present type of motor arrangement. Recent developments in the way of double reduction gearing and worm drive motors giving twice the normal reduction, permit the use of the higher rates of acceleration which Fig. 14 shows is desirable as it follows that with a lower free running speed, the motor capacity necessary is also less to perform a given service.

Shunting of Track Circuit in a Polyphase System of Continuous Inductive Train Control

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Synopsis.—Investigations into shunting of train control track circuits have been made in the field under operating conditions by observing the operation of the primary relay on a locomotive as a train runs into a track circuit in which there is a train ahead or an open switch and similar data have been obtained on the performance of the relay on trains in regular service.

It is intended in this paper to present a method for predetermining the shunting characteristics of train control track circuits. The system discussed is a polyphase system of continuous inductive train control with cab signals employed on double tracked steam roads. Curves are given which describe shunting conditions in train control track circuits and data are also given for comparison describing the shunting of the track relay on the same sections of track.

IN a system of continuous inductive train control the apparatus on the trains on a steam operated railroad is located on the locomotive or tender and consists of a receiving system, visual cab signals, a train controlling mechanism that operates in connection with the automatic air brake equipment on the train, and auxiliary apparatus which include an acknowledging contactor and audible signals. The train controlling mechanism limits the speed of the train at all times to certain predetermined speeds which depend upon traffic conditions and the distance a train has traveled in a block. A failure on the part of the engineman to control the speed of the train properly results in an automatic application of the brakes as soon as the maximum allowable speed has been exceeded. After an automatic application has been made the brakes cannot be released until the speed of the train has been reduced below the maximum speed. When a train is traveling on clear track a clear signal indication is given in the cab and the speed of the train is limited to a safe speed which in the case of a passenger train may be 70 mi. per hr.; when the train enters a caution block the cab signal changes giving a caution or medium speed indication and the automatic controlling mechanism operates to enforce a gradual reduction in speed until the speed has been reduced to below 20 mi. per hr. at the exit end of the block. As a train passes from a caution into an occupied block the signal changes to a danger or slow-speed indication and the limitation of 20 mi. per hr. is maintained as long as the block is occupied by a train ahead.

The cab signals and speed controling mechanism are under the control of a three position a-c. primary relay. When the train is traveling under clear conditions the relay is in its normally energized position; when the train passes into a caution block the relay operates to the reverse position and when it is in an occupied block or a block in which there is an open switch the relay assumes its deenergized position and releases the normal or reverse contacts. The primary relay is under the control of an influence obtained inductively, by means of receivers on the locomotive, from alternating current flowing in the rails of the track.

The apparatus along the track includes the usual a-c. track circuit, modified slightly for train control purposes, and upon this is superimposed a so-called "line circuit." The actual current flowing in the rails consists of two components of current, one due to a voltage impressed on the circuit from the track circuit transformer and the other is due to voltage from a transformer in the line circuit. These two components of currents will be considered separately and will be referred to hereafter simply as "track circuit current" and "line circuit current." The wayside circuits are shown schematically in the diagram in Fig. 1 and may be traced as follows:—Track circuit current flows from the track circuit transformer which is located at the exit end of the block through a limiting impedance and a pole changer to one of the rails of the track, along the rail to the opposite end of the block through a variable resistance unit and windings of the track relay to the other rail, back along the rail and through the pole changer to the transformer. The relay is normally energized by current flowing in the track and local windings as shown in the diagram; the track windings receive current from the rails and the local windings

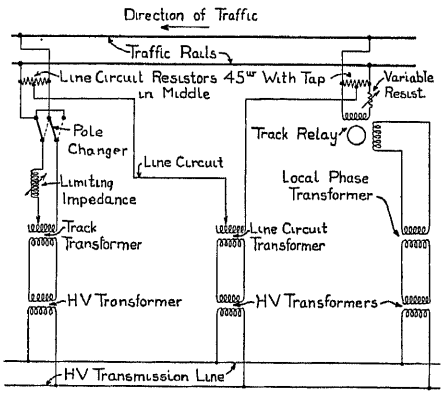

FIG. 1—TRAIN CONTROL TRACK CIRCUIT

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are energized by current from the local phase transformer. The track relay is the usual a-c. rotor type relay employed in railroad signaling which operates in three positions and requires the use of the pole changer in the track circuit to give normal and reverse operation. The normal and reverse control also permits of three position operation of the primary relay which is a similar two element relay of the rotor type. When a block is occupied by a train the current in the rails flows from one rail to the other through the wheels and axles of the train and on account of the very low impedance of the path through the wheels and axles most of the current is shunted from the track relay which causes it to become deenergized sufficiently to release its front contacts. Circuits through the relay contacts control the operation of wayside signals in the usual manner. Line circuit current flows from the line circuit transformer to the middle point of a comparatively high resistance bridged across the rails at the relay end of the block, through the two halves of the resistance and along the rails of the track in multiple, through a similar resistance at the other end of the block to the middle point of the resistance unit and through a line wire back to the transformer. From the description of the circuits it is evident that track circuit current flows away from the transformer on one rail of the track and back on the other rail, that is, the current flows in opposite directions in the two rails whereas the line circuit current is evenly divided between the rails and flows in the same direction in each rail. The track circuits are adjusted for normal operation under clear or caution conditions so that there will be 0.8 ampere in the rails at the relay end of the circuit as a train enters the block and the line circuit is adjusted to give total line circuit current 0.8 ampere or 0.4 ampere in each rail.

There are two receivers located on the locomotive just ahead of the front wheels called track circuit receivers and a similar pair of receivers farther back on the locomotive or on the tender known as line circuit receivers. The receivers are supported a few inches above the rails of the track and coils in each pair of receivers are connected in series. The connections are such that, on account of the direction of the flow of current in the rails, the track circuit receivers are energized inductively by track circuit current and are not influenced by line circuit current and the line circuit receivers are energized by line circuit current and are not affected by current in the track circuit. There is a two-circuit vacuum tube amplifier with four tubes employed in the locomotive equipment to amplify the small voltages induced in the receiver coils. The input circuits of the amplifier are connected separately to the front and rear receivers and the output circuits are connected to corresponding windings of the primary relay. The amplifying apparatus is carefully adjusted so that when the track circuit and line circuit currents in the rails are in time phase, the currents in the relay windings will also be in phase in which case no torque will be developed on the rotor shaft of the relay. If the phase of the current in either the track circuit or the line circuit is varied the corresponding current in the relay follows the phase of the rail current. The phase displacement between the currents in the relay windings under any condition of operation is therefore the same as the phase displacement between the currents in the rails. The size of the current in the relay windings relative to the corresponding rail currents is shown in Fig. 2.

Conditions of the Track. The rails of the track are A. S. C. E. section, 100 lb. per yd., bonded with 2 No. 6 copper-clad bond wires 54 in. long having a loop impedance 0.25 ohm per 1000 ft., power factor 0.5, and the ballast is mostly stone ballast having a resistance varying between 5 ohms and 20 ohms per 1000 ft. of

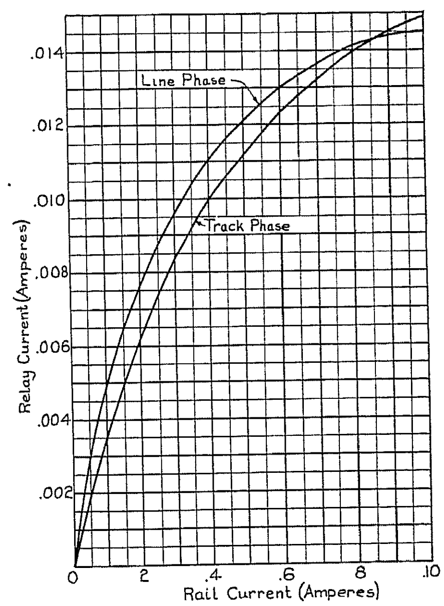

FIG. 2—RELATION BETWEEN CURRENT IN THE RELAY AND CURRENT IN THE RAILS

track. The leakage resistance of two rails in multiple to ground is taken as 2 ohms per 1000 ft. in wet weather and 12 ohms per 1000 ft. in dry weather. The length of the track circuit is 6000 ft.

Characteristics of the Track Relay. Local Phase: Impedance 440 ohms, power factor 0.656; current at 110 volts, 0.25 ampere; phase of current relative to voltage $\overline{\angle}$ 49 deg.

NOTE: The inverted angle sign $\overline{\angle}$ indicates a lagging current or voltage whereas the usual angle sign $\angle$ indicates a leading current or voltage relative to the voltage at the secondary of the transformer. This notation will be employed hereafter in tabulating currents or voltages to describe phase relations.

Track Phase: Impedance 0.64 ohm, power factor 0.656; operating currents with 90 deg. phase displacement. Current to pick up relay to make front stop, 0.22 ampere. Current to pick up relay to close front

contacts, 0.19 ampere. Current to allow relay to release its contacts, 0.11 ampere.

Adjustment of the Track Circuit. On a steam operated road without train control, the track circuit would be adjusted under wet weather conditions with a limiting impedance of 4 ohms but with this adjustment when a train is entering the block there would not be the required current 0.8 ampere in the rails for the operation of the train control equipment. To increase the current in the rails the amount of limiting impedance might be reduced but it would be better for the purpose of improving the shunting, to retain the 4 ohms

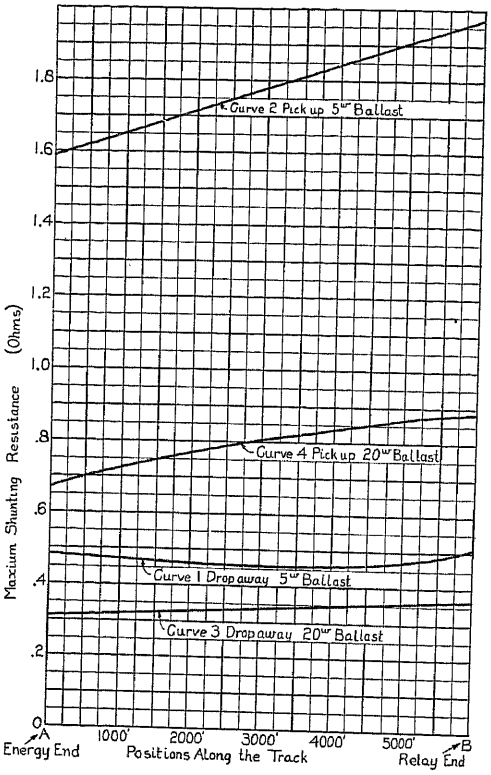

FIG. 3—MAXIMUM SHUNTING RESISTANCES AFFECTING THE TRACK RELAY AS A TRAIN PASSES THROUGH THE BLOCK

limiting impedance and increase the voltage on the track trasformer to give 0.88 ampere, (*i. e.,* 0.8 ampere + 10 per cent to allow for drop in transmission line voltage) and insert a variable resistance in series with the track relay as shown in Fig. 1 to limit the current in the relay sufficiently to give satisfactory normal operation.

Without considering train control, minimum operation of the track relay would be obtained with 3.1 volts at the transformer giving a current 0.26 $\nwarrow$ 117 deg. 33 min. ampere in the relay but to get sufficient current in the rails for train control operation the voltage will have to be increased to 7 volts which gives 0.875 $\nwarrow$ 106 deg. 41 min. ampere in the rails as a train enters the block. The variable resistance in series with the relay is then adjusted when the block is unoccupied to 1.75 ohms giving 0.316 $\nwarrow$ 101 deg. 24 min. ampere in the relay (equivalent current at 90 deg. phase displacement 0.25 ampere). With this adjustment in dry weather when the ballast resistance is 20 ohms per 1000 ft. the current in the relay will increase to 0.706 $\nwarrow$ 75 deg. 7 min. ampere (equivalent current at 90 deg. phase displacement 0.311 ampere) and the current in the rails at the relay end of the circuit as a train enters the block will be 1.185 $\nwarrow$ 85 deg. 34 min. amperes.

Shunting of the Track Relay. Ordinarily with a properly adjusted track circuit when a train enters a block the track relay becomes shunted but in the case of a poorly adjusted circuit under adverse rail conditions it might happen that the relay would not shunt or if the relay shunts properly as a train enters a high shunting resistance might allow the relay to pick up and the train loses its shunt. To determine the shunting characteristics of the track circuit, calculations have been made which show the maximum shunting resistance which will cause the relay to release its contacts and also the resistance which will just allow the relay to pick up again as the train passes through the block. The curves 1 and 3 in Fig. 3 show the maximum shunting resistances for different positions along the track throughout the entire length of the block which will cause the relay to release its contacts and curves 2 and 4 resistances which will allow the relay to pick up to just close its front contacts.

In Table I numerical values are given of the data shown on the curves and also values of current in the relay when the corresponding maximum shunting resistances are connected across the rails. The formulas employed in calculating these maximum shunting resistances at intermediate positions in the block are given in Appendix I.

Characteristics of the Primary Relay. Operating torque on rotor shaft with 90 deg. phase displacement:

To cause sector to operate to front stop 0.45 in. - oz.

To pick up to just make front contacts 0.38 in. - oz.

To release front contacts 0.24 in. - oz.

The relation between torque and currents in the relay is expressed by the following equation:

$$T = I_L \, I_T \, K \sin \phi$$

Where T = Torque on rotor shaft

I_L = Current in line phase

I_T = Current in track phase

ϕ = Difference in phase between I_L and I_T

K = 4500

The value of K is practically constant for all operating conditions.

If the size of the line circuit current in the rails is known at any position on the track the operating current in the rails in the track circuit can be determined at 90 deg. phase displacement to produce any required torque in the primary relay. To accomplish this, knowing the line current in the rails, the corresponding current in the relay is determined from curves in Fig. 2 and knowing the torque (as given above for pick-up and drop-away conditions) the current in the track

TABLE I
MAXIMUM SHUNTING RESISTANCE AS AFFECTING OPERATION OF THE TRACK RELAY

Positions along the track	5 ohm ballast			
	Maximum shunting resistance (ohms)		Current in relay when shunt is applied (amperes)	
	Pick-up	Drop-away	Pick-up	Drop-away
At *A* end	1.585	0.485	0.21 $\overline{\diagdown}$ 115 deg. 11 min.	0.113 $\overline{\diagdown}$ 126 deg. 20 min.
1500 ft. from *A*	1.68	0.468	0.21 $\overline{\diagdown}$ 110 deg. 20 min.	0.116 $\overline{\diagdown}$ 120 deg. 6 min.
3000 ft. from *A*	1.783	0.459	0.223 $\overline{\diagdown}$ 107 deg. 39 min.	0.121 $\overline{\diagdown}$ 114 deg. 17 min.
4500 ft. from *A*	1.87	0.464	0.224 $\overline{\diagdown}$ 107 deg. 23 min.	0.122 $\overline{\diagdown}$ 113 deg. 19 min.
At *B* end	1.97	0.505	0.225 $\overline{\diagdown}$ 106 deg. 28 min.	0.123 $\overline{\diagdown}$ 112 deg. 46 min.

Positions along the track	20 ohm ballast			
	Maximum shunting resistance (ohms)		Current in relay when shunt is applied (amperes)	
	Pick-up	Drop-away	Pick-up	Drop-away
At *A* end	0.672	0.314	0.227 $\overline{\diagdown}$ 105 deg. 51 min.	0.123 $\overline{\diagdown}$ 112 deg. 3 min.
1500 ft. from *A*	0.75	0.327	0.251 $\overline{\diagdown}$ 98 deg. 10 min.	0.134 $\overline{\diagdown}$ 104 deg. 5 min.
3000 ft. from *A*	0.81	0.34	0.263 $\overline{\diagdown}$ 95 deg. 30 min.	0.141 $\overline{\diagdown}$ 99 deg. 30 min.
4500 ft. from *A*	0.855	0.356	0.275 $\overline{\diagdown}$ 92 deg. 44 min.	0.148 $\overline{\diagdown}$ 97 deg. 4 min.
At *B* end	0.887	0.366	0.29 $\overline{\diagdown}$ 89 deg. 53 min.	0.156 $\overline{\diagdown}$ 93 deg. 51 min.

circuit windings of the relay can be determined from the above formula. The track circuit rail current is then determined from the curve. Numerical values of track circuit currents to give pick-up and drop-away of the relay with a train at different positions on the track will be given after a study has been made of the line circuit.

Current in the Rails under the Receivers. Most of the current in the line circuit flows through the rails in

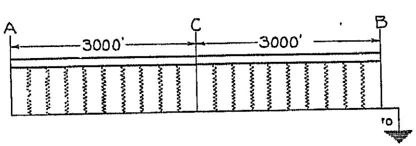

FIG. 4—EVENLY DISTRIBUTED LEAKAGE BETWEEN TWO RAILS IN MULTIPLE AND GROUND

multiple but there is a small amount of current that flows through the ground as shown in Fig. 4. The leakage current flows from the rails to ground in one-half of the circuit from *A* to *C* and flows back from the ground into the rails in the other half of the circuit from *C* to *B*. Tests have been made in the field of the amount of current flowing in the rails throughout the length of a block with a vacuum tube testing apparatus used in connection with a search coil on a laminated iron structure that was placed over the rail. The curves obtained show that the current in the rails follows very closely to the shape of the common catenary or cosh curve and for that reason the conductance to ground is assumed to be evenly distributed and line circuit currents have therefore been computed from well known hyperbolic formulas. The condition shown in Fig. 4 may also be represented as shown in Fig. 5 in which the ground is assumed to have zero resistance and is represented as a neutral plane. For uniformity in the use of formulas in making calculations the line circuit may be considered as if it were a two-conductor circuit 3000 ft. in length having evenly distributed leakage giving the same attenuation in Fig. 5 as in Fig. 4. The loop impedance is taken as 0.125 ohm per 1000 ft., and leakage resistance of twice the values given above, *i. e.*, 4 ohms per 1000 ft. in wet weather and 24 ohms in dry weather. The attenuation in the latter case is so small that it may be neglected. The complete line circuit shown in Fig. 1 contains mostly resistance and for that reason the current from the transformer as it enters the rails at either end of the block is assumed to be in phase with the voltage at the transformer and it is further assumed that the voltage at the secondaries of the transformers supplying the track and line circuits and the local circuit of the track relay are in phase. Calculations have been made of

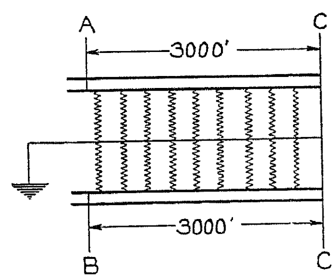

FIG. 5—ANOTHER ARRANGEMENT TO DESCRIBE CONDITION SHOWN IN FIG. 4

the line circuit current in the rails at different positions along the track and the results are given in Table II. The table also shows corresponding values of current in the relay taken from the curves in Fig. 2.

Having determined the line circuit currents in the relay and knowing the torque characteristics the corresponding currents in the track circuit windings can be determined by use of the formula given above assuming 90 deg. phase displacement. For a train at different positions on the track numerical values of the current have been computed to cause the relay to operate to its front stop, to pick up to just close its front contacts, and to release the contacts. These

TABLE II
LINE CIRCUIT CURRENT IN THE RAILS AND CORRESPONDING CURRENT IN THE RELAY
Ballast 5 Ohms per 1000 ft.

Positions along the track	Currents in rails	Current in relay
At A end........	0.88 ∖ 0 deg. ampere	0.0144 ampere
1000 ft. from A..	0.87 ∖ 1 deg. ampere	0.01435 ampere
2000 ft. from A..	0.86 ∖ 3 deg. ampere	0.0143 ampere
3000 ft. from A..	0.817 ∖ 6 deg. 30 min. ampere	0.0142 ampere
4000 ft. from A..	0.86 ∖ 3 deg. ampere	0.0143 ampere
5000 ft. from A..	0.87 ∖ 1 deg. ampere	0.01435 ampere
At B end........	0.88 ∖ 0 deg. ampere	0.0144 ampere

Ballast 20 ohms per 1000 ft.

In this case the current in the rails at any position on the track is 0.88 0 deg. ampere and the current in the relay is 0.0144 ampere.

and release its contacts. The operation of the relay would immediately start the train controlling mechanism in operation to control the speed of the train automatically. In practise a shunt across the rails may be through a circuit controller at an open switch or it may be due to a train ahead in the same block.

Two conditions of shunting have been considered; first, with a forward train the middle of the block and the following train entering and approaching the train ahead; second, with a forward train at the exit end of the block and the rear train entering and proceeding into the block. The most difficult condition of shunting has been considered in which it is assumed that the resistance through the wheels and axles on the rear train is negligible. In each case calculations have been made to determine the maximum shunting resistance through the wheels and axles of the forward train which will cause the pick-up or the drop-away of the primary relay on the rear train when the ballast resistance is 5 ohms and also when it is 20 ohms per 1000 ft. of track. The results of the calculations are plotted in curves in Figs. 6 and 7. Curves in Fig. 6 are for the case where the forward train is in the middle of the block and Fig. 7 where the forward train is at the leaving end of the block. In both figures, curves 1 and 2 show the maximum resistances of the shunt of the forward train which

TABLE III
PICK UP AND DROP AWAY CHARACTERISTICS OF PRIMARY RELAY IN TERMS OF TRACK CIRCUIT CURRENT IN THE RELAY AND CORRESPONDING CURRENT IN THE RAILS AT 90 DEG. PHASE DISPLACEMENT

—	Pick-up to just make front stop		Pick-up to just make front contacts		Drop-away to release contacts	
Positions along the track	Current in relay (amperes)	Current in rails (amperes)	Current in relay (amperes)	Current in rails (amperes)	Current in relay (amperes)	Current in rails (amperes)
At A end..............	0.00695	0.233	0.00587	0.186	0.0037	0.11
1000 ft. from A........	0.00697	0.234	0.00589	0.187	0.00372	0.111
2000 ft. from A........	0.007	0.235	0.00592	0.188	0.00373	0.112
3000 ft. from A........	0.00705	0.236	0.00596	0.189	0.00376	0.113
4000 ft. from A........	0.007	0.235	0.00592	0.188	0.00373	0.112
5000 ft. from A........	0.00697	0.234	0.00589	0.187	0.00372	0.111
At B end..............	0.00695	0.233	0.00587	0.186	0.0037	0.11

values are given in Table III together with corresponding track circuit currents in the rails which have been taken from the curves in Fig. 2. In making track circuit calculations to determine the performance of a track relay the pick-up and drop-away characteristics are usually given in terms of the current in the track and local windings of the relay at 90 deg. phase displacement. The data in Tables II and III give the operating characteristics of the primary relay in terms of line circuit and track circuit current in the rails of the track under the receivers at 90 deg. phase displacement, and are intended to be used in a similar manner in making train control track circuit calculations. For instance, if the currents in the rails under the receivers are computed and also their phase relation for a train at any position on the track, the equivalent track circuit current at 90 deg. phase displacement may then be determined and compared with the data in the tables to obtain a knowledge of the performance of the relay.

In this discussion the data in the tables have been employed in connection with formulas given in Appendix II in making calculation of the shunting characteristics of the circuit.

Shunting of the Track as Affecting the Primary Relay. In a train control track circuit energy is always fed to the rails at the end of the block ahead of the train when the block is occupied. If a shunt is connected across the rails at any position in the block in advance of the train the track circuit current would flow through the shunt path and there would be practically no track circuit current under the receivers on the train with the result that the primary relay would become deenergized

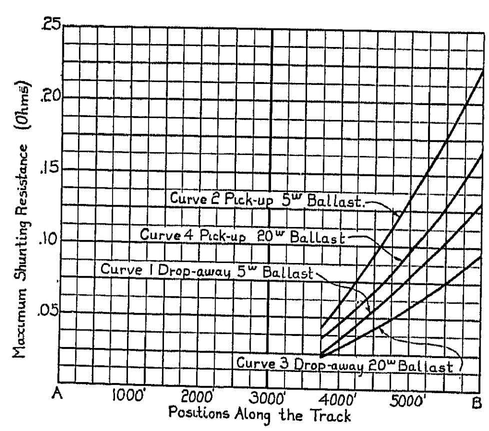

FIG. 6—CURVES SHOWING MAXIMUM SHUNTING RESISTANCES WHEN FORWARD TRAIN IS IN THE MIDDLE OF A BLOCK AND A FOLLOWING TRAIN IS ENTERING AND APPROACHING FROM THE RELAY END

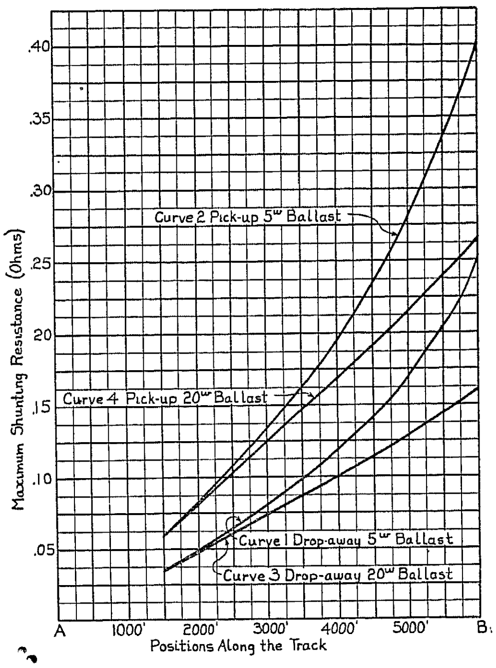

FIG. 7—CURVES SHOWING MAXIMUM SHUNTING RESISTANCE WHEN FORWARD TRAIN IS AT THE ENERGY END OF A BLOCK AND A FOLLOWING TRAIN ENTERING AND APPROACHING FROM THE RELAY END

will prevent the relay on the rear train from picking up and the resistances which will cause the relay to drop away respectively when the ballast is 5 ohms per 1000 ft. and curves 3 and 4 give the maximum resistances when the ballast is 20 ohms per 1000 ft. Numerical data from which these curves are plotted and also corresponding values of track circuit current in the rails under the receivers on the rear train are given in Tables IV and V.

The method of making these shunting calculations in train control track circuits is described in Appendix II.

CONCLUSIONS

In Fig. 3 the curves 3 and 4 describe the shunting of the track relay as a train passes through the block during dry weather conditions. The resistance of the shunt must be less than 0.366 ohm as shown on curve 3 when the train enters the block to cause the relay to release its contacts and as the train proceeds the resistance must remain less than the resistances shown on curve 4 to prevent the relay from picking up. If the relay should pick up, the shunting resistance must decrease again below the values shown on curve 3 to cause the relay to release its contacts.

The curves in Figs. 6 and 7 describe the shunting

TABLE IV

TRAIN CONTROL, MAXIMUM SHUNTING RESISTANCES FORWARD TRAIN IN MIDDLE OF THE BLOCK

Position of rear train	Maximum shunting resistance (ohms) Pick-up	Maximum shunting resistance (ohms) Drop-away	Current in rails under receivers (amperes) Pick-up	Current in rails under receivers (amperes) Drop-away
	5 ohm ballast			
At B end............	0.227	0.132	0.285 ⦣ 139 deg. 14 min.	0.186 ⦣ 143 deg. 50 min.
5000 ft. from A........	0.132	0.078	0.284 ⦣ 138 deg. 49 min.	0.181 ⦣ 143 deg. 5 min.
4000 ft. from A........	0.058	0.0346	0.255 ⦣ 135 deg. 27 min.	0.143 ⦣ 141 deg. 12 min.
	20 ohm ballast			
At B end............	0.168	0.096	0.263 ⦣ 134 deg. 58 min.	0.163 ⦣ 137 deg. 38 min.
5000 ft. from A........	0.097	0.058	0.256 ⦣ 133 deg. 16 min.	0.16 ⦣ 136 deg. 33 min.
4000 ft. from A........	0.045	0.029	0.252 ⦣ 132 deg. 27 min.	0.152 ⦣ 136 deg. 20 min.

TABLE V

TRAIN CONTROL, MAXIMUM SHUNTING RESISTANCES FORWARD TRAIN AT ENERGY END OF BLOCK

Position of rear train	Maximum shunting resistance (ohms) Pick-up	Maximum shunting resistance (ohms) Drop-away	Current in rails under receivers (amperes) Pick-up	Current in rails under receivers (amperes) Drop-away
	5 ohm ballast			
At B end............	0.405	0.25	0.312 ⦣ 143 deg. 27 min.	0.208 ⦣ 148 deg. 1 min.
4000 ft. from A........	0.196	0.118	0.286 ⦣ 138 deg. 53 min.	0.172 ⦣ 142 deg. 26 min.
2000 ft. from A........	0.082	0.049	0.257 ⦣ 136 deg. 3 min.	0.17 ⦣ 138 deg. 52 min.
	20 ohm ballast			
At B end............	0.266	0.161	0.262 ⦣ 134 deg. 43 min.	0.167 ⦣ 138 deg. 42 min.
4000 ft. from A........	0.168	0.101	0.26 ⦣ 134 deg. 19 min.	0.164 ⦣ 137 deg. 54 min.
2000 ft. from A........	0.083	0.050	0.261 ⦣ 138 deg. 28 min.	0.163 ⦣ 137 deg. 38 min.

requirements for safe operation of the train control equipment. For instance, during dry weather conditions when there is a train in the middle of a block and a following train is entering the block, curve 3 in Fig. 6 shows that the resistance of the shunt of the forward train must be less than 0.096 ohm to cause the primary relay on the rear train to release its contacts and the resistance must remain less than the values shown on curve 4 to prevent the relay from picking up as the train proceeds into the block. If the relay should pick-up the shunting resistance must be reduced to a value less than those shown on curve 3 to cause the relay to drop away again.

In the ordinary track circuit, the wheels of a train shunt out the track relay in series with the rails of the track but in the case of a forward train shunting current from a rear train there is only the impedance of the rails between the two trains and the impedance through the wheels and axles of the rear train to be shunted. The effect of the shunting on the primary relay is not as good as the shunting of the track relay and the shunting effect on the primary relay on a following train becomes poorer as the train runs closer to the train ahead.

In short train control track circuits, the condition of the ballast has little effect on the shunting of the primary relay but in longer circuits, a mile or more in length, the ballast resistance has a considerable effect. The curves show that the shunting is better during wet weather than it is under dry weather conditions.

Appendix I

Intermediate Shunting in A-c. Steam Road Track Circuits

It is possible to determine the maximum shunting resistance in either a-c. steam or electric road track circuits by using the general formula for shunting.

$$G = \frac{E\,Y}{I_S} - K$$

This formula in either case may be employed when a shunt is connected at either end of a track circuit or at any intermediate position along the track. In solving any problem for shunting it is first necessary to determine the values of Y and K and for this purpose formulas have been given in a previous article[2] for determining these values in a steam road track circuit in cases where the shunt is applied at either end of the circuit. It is intended in this appendix to derive the formulas for Y and K that have been used in making calculations of shunting of the track relay at intermediate positions along the track.

The diagram in Fig. 8 is the ordinary steam road track circuit in which $A\,B$ is a track section to which there is a shunt connected across the rails at an intermediate position C. The circuit shown in Fig. 9 is the same as the circuit in Fig. 8 except that the transformer has been transposed from its usual position at A to position C and is connected in series in the rails on the energy side of the shunt.

The following is a description of the symbols employed most of which are shown in Fig. 8, which we will

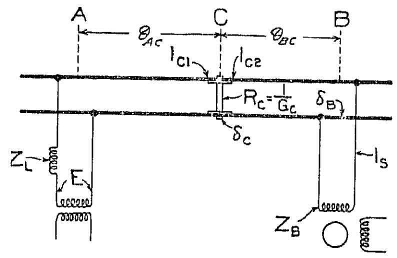

Fig. 8

call the normal circuit, or that in Fig. 9, which will be referred to as the reverse circuit.

E = voltage at transformer (standard phase), in both the normal and reverse circuits.

i = equivalent current in the relay at 90 deg. phase displacement, which will just cause the relay to drop away or in determining loss of train shunt it is the value of current which just allows the relay to pick up sufficiently to make its contacts.

G_C = minimum shunting conductance when a shunt is applied at C.

R_C = maximum shunting resistance when shunt is applied at C.

The above quantities are considered as real quantities whereas those that follow are complex quantities.

Z_B = impedance of relay and leads to track.

Z_L = limiting impedance including leads to track.

z_0 = surge impedance of the track.

θ = hyperbolic angle subtending portions of the track as indicated by subscripts.

$\delta_B = \tanh^{-1} \dfrac{Z_B}{z_0}$ = position angle at B in normal circuit

$\delta_C = \delta_B + \theta_{BC}$ = position angle at C in normal circuit

I_S = current in relay when shunt is applied.

I_{C2} = current in rails on relay side of shunt in normal circuit.

I_{C1} = current in rails on energy side of shunt in normal circuit.

$\delta_A' = \tanh^{-1} \dfrac{Z_L}{z_0}$ = position angle at A in reverse circuit.

$\delta_C' = \delta_A' + \theta_{AC}$ = position angle at C in reverse circuit.

I_A' = current in limiting impedance in reverse circuit.

I_{C1}' = current flowing through transformer in reverse circuit (impedance of transformer secondary is assumed negligible).

2. *Shunting in A-C. Track Circuits*, By C. F. Estwick, A. I. E. E. Journal, December 1921, p. 919.

From the theory of the reverse circuit it will be understood that the current I_{C1} in Fig. 8 is the same as current I_A' in the reverse circuit in Fig. 9. With this principle

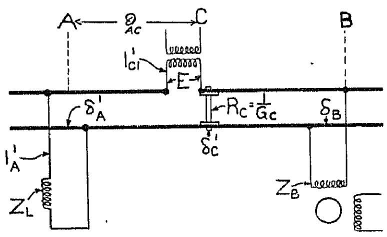

Fig. 9

in mind the following algebraic solution may be understood by reference to the diagrams.

From Fig. 8

$$I_{C2} = I_S \times \frac{\cosh \delta_C}{\cosh \delta_B} \tag{1}$$

and from Fig. 9

$$I_{C1}' = \frac{E}{\dfrac{R_C\, z_0 \tanh \delta_C}{R_C + z_0 \tanh \delta_C} + z_0 \tanh \delta_C'} \tag{2}$$

and $$I_{C1} = I_A' = I_{C1}' \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \tag{3}$$

From Fig. 8

$$I_{C2} = I_{C1} \times \frac{R_C}{R_C + z_0 \tanh \delta_C} \tag{4}$$

Combining the above equations

$$I_S \times \frac{\cosh \delta_C}{\cosh \delta_B} = \frac{E}{\dfrac{R_C\, z_0 \tanh \delta_C}{R_C + z_0 \tanh \delta_C} + z_0 \tanh \delta_C'} \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \times \frac{R_C}{R_C + z_0 \tanh \delta_C} \tag{5}$$

Simplifying the second member

$$I_S \times \frac{\cosh \delta_C}{\cosh \delta_B} = \frac{E\, R_C}{R_C(z_0 \tanh \delta_C + z_0 \tanh \delta_C') + z_0^2 \tanh \delta_C \tanh \delta_C'} \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \tag{6}$$

For simplicity substitute

$$a = \frac{\cosh \delta_C}{\cosh \delta_B} \quad b = z_0 \tanh \delta_C \quad c = z_0 \tanh \delta_C'$$

$$d = \frac{\cosh \delta_A'}{\cosh \delta_C'} \tag{6a}$$

Then $$I_S\, a = \frac{E\, R_C\, d}{R_C\,(b + c) + b\, c} \tag{7}$$

Remembering that $G_C = 1/R_C$

$$I_S\, a = \frac{E\, d}{G_C\, b\, c + (b + c)} \tag{8}$$

Whence $$G_C = \frac{E\, d}{I_S\, abc} - \frac{b + c}{bc} \tag{9}$$

Expanding we have

$$G_C = \frac{E \cosh \delta_A' \cosh \delta_B}{I_S \cosh \delta_C \cosh \delta_C'\, z_0^2 \tanh \delta_C \tanh \delta_C'} - \frac{z_0\,(\tanh \delta_C + \tanh \delta_C')}{z_0^2 \tanh \delta_C \tanh \delta_C'} \tag{10}$$

or $$G_C = \frac{E \cosh \delta_A' \cosh \delta_B}{I_S\, z_0^2 \sinh \delta_C \sinh \delta_C'} - \frac{\tanh \delta_C + \tanh \delta_C'}{z_0 \tanh \delta_C \tanh \delta_C'} \tag{11}$$

This formula is used for determining the minimum conductance or maximum resistance of a shunt at an intermediate position on the track.

When the shunt is transferred to the A end of the track, this formula reduces to

$$G_A = \frac{E \cosh \delta_B}{I_S\, Z_L\, z_0 \sinh \delta_A} - \frac{Z_L + z_0 \tanh \delta_A}{Z_L\, z_0 \tanh \delta_A} \tag{12}$$

And when the shunt is at the B end the formula becomes

$$G_B = \frac{E \cosh \delta_A'}{I_S\, Z_B\, z_0 \sinh \delta_B'} - \frac{Z_B + z_0 \tanh \delta_B'}{Z_B\, z_0 \tanh \delta_B'} \tag{13}$$

From the above formula for intermediate shunting we then have

$$Y = \frac{\cosh \delta_A' \cosh \delta_B}{z_0^2 \sinh \delta_C \sinh \delta_C'} \tag{14}$$

$$K = \frac{\tanh \delta_C \tanh \delta_C'}{z_0 \tanh \delta_C \tanh \delta_C'} \tag{15}$$

Having determined Y and K the maximum shunting resistances and corresponding currents in the relay can be computed in the manner already described in the previous article referred to above, however, to make this discussion more complete the formulas employed are given below.

Let γ = Slope of track phase current in relay (degrees)
β = Slope of local phase current in relay (degrees)
$\phi = \beta - \gamma$ = Phase displacement (degrees)
y = Size of Y
v = Slope of Y (degrees)

m, n, e, and f are numerical values obtained from the following equations

$$\frac{E\, y}{i} \angle (v - \beta) = m + j\, n \text{ and } - K = e + j\, f \tag{16}$$

Then, when ϕ is positive (as it is in all cases considered above),

$$G_C = e - \frac{n}{2} \pm \sqrt{\left(\frac{n}{2}\right)^2 - m f - f^2} \qquad (17)$$

In this formula the proper sign before the radical is used to determine G_C as a positive quantity.

Then $R_C = 1/G_C$

$$\gamma = v - \tan^{-1}\left(\frac{-f}{G_C - e}\right) \qquad (18)$$

and

$$I_S = \frac{i}{\sin\phi} \angle \gamma \qquad (19)$$

In the last formula $\sin\phi$ is always taken as positive.

Numerical examples given in the previous paper will show more clearly how these formulas are employed.

Appendix II

Shunting in Train Control Track Circuits

In the train control track circuit shown schematically in the diagram Fig. 10 there are two trains in the block at positions C and D. It is required to determine the resistance of the shunt through the wheels and axles of

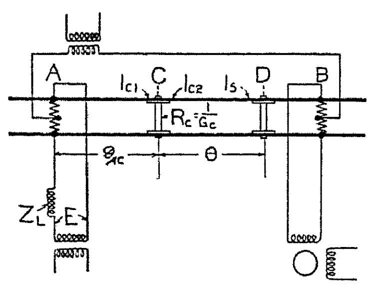

Fig. 10

the train at C which will just cause the primary relay on the train at D to release its front contacts or the resistance of the shunt which will just allow the relay to pick up and close the contacts. The resistance of the shunt of the following train at D is assumed to be negli-

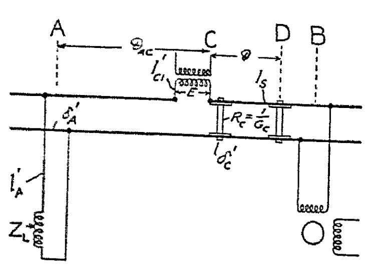

Fig. 11

gible and short-circuits the track relay and the rails in the rear of the train. The formulas for shunting are derived in a manner very similar to those in Appendix I for shunting of the track relay at an intermediate position in the block. If the line circuit in Fig. 10 is neglected it can be seen that the circuit in Fig. 11 is the same as the circuit in Fig. 10 except that the transformer has been transposed from its normal position at A in Fig. 10 to position C as shown in Fig. 11. The symbols employed herein are the same as those in Appendix I except as follows:

I_S = track circuit current in the rails under the front receivers on the train at D and is the same as the short-circuit current through the wheels and axles of the train.

γ = slope of the current I_S.

i = size of pick-up or drop-away track circuit current in the rails under the receivers on the train at D at 90 deg. phase displacement taken from the second and third columns in Table III.

β = slope of line circuit current in the rails under the rear receivers on the train at D given in the second column in Table II.

θ = hyperbolic angle subtending the length of track from C to D.

δ_B and δ_C are not employed in this case.

Referring to the diagram in Fig. 10 we have

$$I_{C2} = I_S \cosh\theta \qquad (1)$$

and from Fig. 11

$$I_{C1}' = \frac{E}{\dfrac{R_C z_0 \tanh\theta}{R_C + z_0\tanh\theta} + z_0 \tanh\delta_C'} \qquad (2)$$

It will be understood that I_{C1} in Fig. 10 is equal to I_A' in Fig. 11, therefore,

$$I_{C1} = I_A' = I_{C1}' \times \frac{\cosh\delta_A'}{\cosh\delta_C'} \qquad (3)$$

From Fig. 10

$$I_{C2} = I_{C1} \times \frac{R_C}{R_C + z_0\tanh\delta_C} \qquad (4)$$

Combining the above equations,

$$I_S\cosh\theta = \frac{E}{\dfrac{R_C z_0\tanh\theta}{R_C + z_0\tanh\theta} + z_0\tanh\delta_C'} \times \frac{\cosh\delta_A'}{\cosh\delta_C'} \times \frac{R_C}{R_C + z_0\tanh\theta} \qquad (5)$$

This equation is similar to equation (5) in Appendix I and treated in the same manner gives the following equations for the minimum conductance of the shunt of the train at C

$$G_C = \frac{E\cosh\delta_A'}{I_S z_0^2 \sinh\theta\sinh\delta_C'} - \frac{\tanh\theta + \tanh\delta_C'}{z_0\tanh\theta\tanh\delta_C'} \qquad (6)$$

Whence

$$Y = \frac{\cosh\delta_A'}{z_0^2\sinh\theta\sinh\delta_C'} \qquad (7)$$

and

$$K = \frac{\tanh\theta + \tanh\delta_C'}{z_0\tanh\theta\tanh\delta_C'} \qquad (8)$$

When the forward train is at A these formulas reduce

to

$$G_A = \frac{E}{I_S Z_L z_J \sinh\theta} - \frac{Z_L + z_0 \tanh\theta}{Z_L z_0 \tanh\theta} \qquad \textbf{(9)}$$

$$Y = \frac{1}{Z_L z_0 \sinh\theta} \qquad \textbf{(10)}$$

$$K = \frac{Z_L + z_0 \tanh\theta}{Z_L z_0 \tanh\theta} \qquad \textbf{(11)}$$

After determining the values of Y and K, the solution is completed in the same manner as in Appendix I employing the formulas **(16)** to **(19)**.

Numerical Example. As an example, consider a case of shunting in which there are two trains in a block, the forward train being in the middle of the section and the following train a distance of 2000 ft. in the rear of the train ahead or at a point 1000 ft. from the entrance end of the block. It is required to determine the maximum shunting resistance through the wheels and axles of the forward train which will cause the primary relay on the rear train to release its front contacts. The loop impedance of the rails is 0.25 ohm per 1000 ft., the ballast resistance from rail to rail is 5 ohms per 1000 ft. and the resistance of the ballast from two rails in multiple to ground is 2 ohms per 1000 ft. of track. The voltage at the line circuit transformer is adjusted so that the total line circuit current from the transformer is 0.88 ampere and the voltage at the track transformer is adjusted to 7 volts. The limiting impedance $Z_L = 4 \angle 83$ deg. ohms.

Line circuit current in the rails under the rear train is $0.87 \nwarrow 1$ deg. ampere as given in Table II. The drop away current in the rails at 90 deg. phase displacement is taken from Table III, $i = 0.111$ ampere.

Let $z = 0.25 \angle 60$ deg. loop impedance of rails per 1000 ft.

$g = 0.2$ conductance of ballast per 1000 ft.

$z_0 =$ surge-impedance of the track

and $\alpha =$ attenuation constant

Then

$$z_0 = \sqrt{z/g} = \sqrt{\frac{0.25 \angle 60°}{0.2}} = 1.12 \angle 30° \text{ ohms}$$

$$\alpha = \sqrt{z\,g} = \sqrt{0.25 \angle 60° \times 0.2} = 0.224 \angle 30° \text{ hyp.}$$

$$= 0.1935 + j\,0.112 = 0.1935 + j\,\underline{0.0713}$$

$$\theta = 2\,\alpha = 0.387 + j\,\underline{0.143}$$

$$\text{and} \quad \delta_A' = \tanh^{-1}\frac{Z_L}{z_0} = \tanh^{-1}\frac{4 \angle 83°}{1.12 \angle 30°}$$

$$= \tanh^{-1} 3.57 \angle 53°$$

Referring to the Chart Atlas of Complex Hyperbolic Functions[3] Table XII_A, we find by inspection from the curves

$$\delta_A' = 0.16 + j\,\underline{0.857}$$

We also have $\theta_{AC} = 3\,\alpha = 0.58 + j\,\underline{0.214}$

and $\delta_C' = \delta_A' + \theta_{AC} = 0.74 + j\,\underline{1.071}$

Referring again to the Chart Atlas we may take out the following functions.

$\sinh\theta = 0.45 \angle 31°\ 30'$.........from Table $X\text{–}XI_A$
$\tanh\theta = 0.43 \angle 27°$.............from Table XII_A
$\cosh\delta_A' = 0.273 \angle 35°$...........from Table $X\text{–}XI_A$
$\sinh\delta_C' = 1.283 \angle 94°\ 20'$........from Table $X\text{–}XI_A$
$\tanh\delta_C' = 1.54 \nwarrow 6°\ 40'$.........from Table XII_A

Employing formulas in Appendix II for train C at an intermediate position in the block.

$$Y = \frac{\cosh\delta_A'}{z_0^2 \sinh\delta_C' \sinh\theta}$$

$$= \frac{0.273 \angle 35°}{1.254 \angle 60° \times 1.283 \angle 94°\ 20' \times 0.45 \angle 31°\ 30'}$$

$$= 0.376 \nwarrow 150°\ 50'$$

$$\text{and } K = \frac{\tanh\delta_C' + \tanh\theta}{z_0 \tanh\delta_C' \tanh\theta}$$

$$= \frac{1.54 \nwarrow 6°\ 40' + 0.43 \angle 27°}{1.12 \angle 30° \times 1.54 \nwarrow 6°\ 40' \times 0.43 \angle 27°}$$

$$= 2.58 \nwarrow 49°\ 50' = 1.665 - j\,1.97$$

or $\quad -K = -1.665 + j\,1.97$

Whence

$y = 0.376 \qquad v = \nwarrow 150°\ 50' \qquad v - \beta = \nwarrow 149°\ 50'$

$$\frac{E\,y}{i} \angle (v - \beta) = \frac{7 \times 0.376}{0.111} \nwarrow 149°\ 50'$$

$$= 23.7 \nwarrow 149°\ 50' = -20.5 - j\,11.95$$

we then have

$m = -20.5 \qquad n = -11.95 \qquad e = -1.665 \qquad f = 1.97$

$$G_C = e - \frac{n}{2} \pm \sqrt{\left(\frac{n}{2}\right)^2 - mf - f^2}$$

$$= -1.665 + 5.975 + \sqrt{5.975^2 + 40.4 - 3.88} = 12.83 \text{ mhos}$$

$R_C = 0.078$ ohms

$$\tan^{-1}\left(\frac{-f}{G_C - e}\right) = \tan^{-1}\left(\frac{-1.97}{14.49}\right) = \nwarrow 7°\ 45'$$

$$\gamma = v - \tan^{-1}\left(\frac{-f}{G_C - e}\right) = \nwarrow 150°\ 50' - \nwarrow 7°\ 45'$$

$$= \nwarrow 143°\ 5'$$

$$\phi = \beta - \gamma = \nwarrow 1° - \nwarrow 143°\ 5' = +142°\ 5'$$

$$I_S = \frac{i}{\sin\phi} \angle \gamma = \frac{0.111}{0.615} \nwarrow 143°\ 5' = 0.181 \nwarrow 143°\ 5'$$

It may be seen that the above values of R_C and I_S are given in the second and fourth columns in Table IV.

3. Chart Atlas of Complex Circular and Hyperbolic Functions, by A. E. Kennelly, Third Edition, 1924, *Harvard University Press.*

Electric Conduction in Hard Rubber, Pyrex, Fused and Crystalline Quartz

BY HUBERT H. RACE*
Associate, A. I. E. E.

Synopsis.—The study of physical and electrical characteristics of insulating materials is of growing importance to the electrical industry because of the ever increasing potentials employed in electric generating and distributing equipment. The particular problem presented in this paper is related to engineering practise because polarization and conduction both result in the conversion of electric energy into heat. This produces increased local and general heating, which may be contributing causes to the progressive deterioration and final breakdown of the insulation. The constant potential method explained in this paper provides a means for studying the inherent voltage-current-time relations which are masked in experiments using alternating applied potential.

Part of the material contained in this paper was presented by the writer to the faculty of the Graduate School of Cornell University for the degree of Doctor of Philosophy. The investigation was later continued with the joint support of the Hecksher Research Council and the General Electric Company.

Several methods were tried for obtaining conducting surfaces on the specimens for constant potential tests. An improved method was devised for making tests and experimental results on four materials were obtained. Peculiar reversals were observed in the charge and discharge curves for fused quartz.

The summary of experimental results is followed by suggestions for further research along similar lines.

Apparatus and Procedure

A. *New Method of Measurement.*

PREVIOUSLY the most precise measurements of the extremely small currents obtained in d-c. tests on good solid dielectrics have involved the use of a quadrant electrometer as a quantitative measuring instrument.

The erratic shifting of the zero point and changing of the sensitivity of an electrometer led the writer to devise a method of measurement which uses the electrometer as a null indicating device, so that changes in sensitivity do not affect the results. The method used is convenient and accurate for a range from 10^{-12} to 10^{-18} ampere, when the current is changing by only a very small percentage over a period of ten seconds or longer.

The object of the tests reported in this paper was to determine curves of electric current flow as functions of time through certain solid dielectrics after constant potential had either been applied to, or removed from, opposite faces of a flat plate of the sample.

The charge and current curves to be expected when constant potential is applied to such a sample are shown in Fig. 1. The great proportion of the charge is stored almost instantaneously, but because the dielectric is not perfect, the charge collected continues to increase. The curve of charge will approach a straight line whose slope will be zero if the final conductivity is zero, and will be finite if the final conductivity is not zero. The current curve is the first derivative of the charge curve and will have the general character shown. Its shape during the first instants will depend upon the characteristics of the external circuit.

The initial pulse of the current passes in a very small fraction of a second after applying the potential and was not measured in any of the reported tests. For some materials, the stored charge continues to increase for weeks after the potential is applied, and is kept constant. It is this long-time current that has been measured in these tests. When the potential is removed after a long-time charge, the currents are similar but reversed in direction.

The currents obtained are smaller than can be measured with a galvanometer, so that a circuit using a sensitive electrometer was used. The diagram shown in Fig. 2 will help to explain the method of measurement. C_s is the sample to be tested. C_A is an auxiliary air condenser of known capacitance. P is a potentiometer used to vary the potential applied to the lower plate of C_A. The quadrant electrometer, *Q. E.*, is used as a very sensitive electrostatic voltmeter to indicate any potential difference between the ground

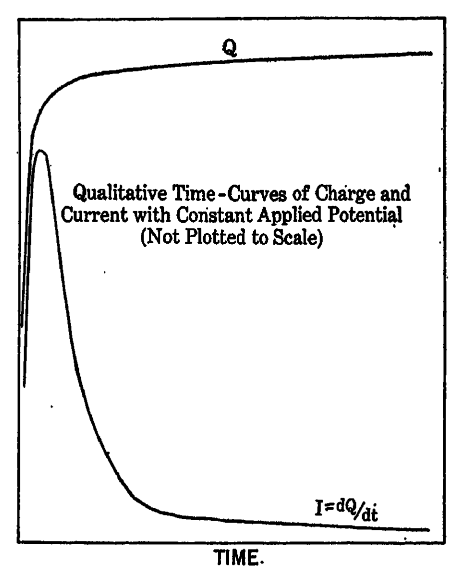

FIG. 1—QUALITATIVE CHARGES AND CURRENT CURVES

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For numbers references see Bibliography.

Presented at Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

and the isolated system comprising the upper surface of the active area of C_s and the upper plate of C_A.

Before applying potential to the lower plate of C_s, the upper system is grounded by closing the ground switch shown in Fig. 2. Then when potential is applied, the initial rush of current is conducted through this ground connection. If the ground connection is removed at any time while current is flowing through the specimen, the result will be an accumulation of charge on the isolated plates of C_s and C_A, (upper system in Fig. 2). This will result in an increasing potential of the isolated system indicated by a movement of the electrometer spot of light.

Assume first that the electrometer is to be used

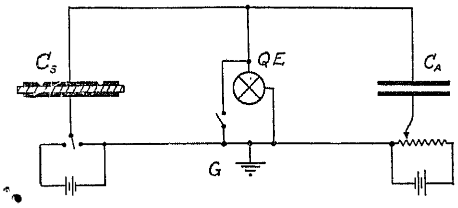


FIG. 2—SIMPLIFIED DIAGRAM OF CONNECTIONS

quantitatively; then the motion of its spot of light should be recorded and interpreted in volts per second, which, when multiplied by the capacitance of the connected system, would give the current flow. However, the difficulties with this method are that the capacitance of the system is difficult to determine accurately, and the capacitance and sensitivity of the electrometer are not constant.

Now, as a different method, suppose that after the ground connection has been removed, the slider on P is

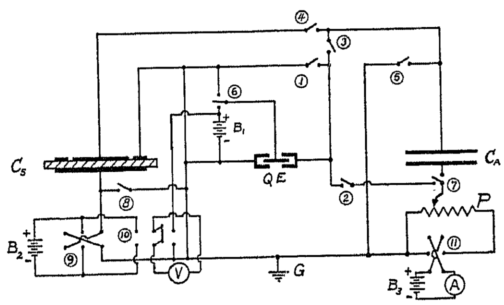


FIG. 3—COMPLETE DIAGRAM OF CONNECTIONS

continually adjusted so as to keep the upper system (though insulated from ground) at ground potential. This is accomplished by so adjusting P that the electrometer spot of light is kept at its zero position. Such an adjustment is possible because any electricity passing from C_s can be drawn onto C_A by properly varying the potential applied to the latter. If at the beginning and end of a certain length of time, the potential of the isolated system is at zero (or any other) potential, all of the current which has passed from C_s in the interval will be collected on C_A. The average value of this current will be given by the equation:

$$i_{ave} = \frac{\Delta q}{\Delta t} = C_A \frac{\Delta e}{\Delta t} = C_A \left(\frac{e_2 - e_1}{t_2 - t_1}\right) \text{ amperes} \quad (1)$$

where C_A is the capacitance in farads of the auxiliary air condenser and $(e_2 - e_1)$ is the change in potential applied to the lower plate of C_A from P during the interval of time $(t_2 - t_1)$, potential being measured in volts and time in seconds.

For all of the tests, the current was considered positive in the direction in which it was normally flowing while a positive potential was applied to the lower plate of C_s. To measure a positive current, it was necessary to apply a negative potential to the lower plate of C_A. When the current was reversed, for example during discharge after positive charge, the polarity of P had to be reversed in order to keep the potential of the isolated system zero. During a reading, continuous observation of the electrometer scale was necessary; therefore, the set-up was so arranged that all switching was remotely controlled from the observer's position behind the scale.

The complete diagram of connections is shown in Fig. 3. The positions of all the switches for different conditions of test are given in Table I.

TABLE I
SWITCH POSITIONS FOR DIFFERENT EXPERIMENTAL CONDITIONS

Switch number	Positions A	Positions B	Positions C	Experimental conditions
1	open	closed	open	A = Before starting a run and during discharge readings.
2	open	open	open	
3	closed	closed	closed	B = At very beginning of a run and between charge readings.
4	closed	closed	closed	
5	open	open	open	C = During readings for charge curve.
6	down	down	down	
7	up	up	up	
8	closed	open	open	
9	open	right	right	
10	open	open	open	
11	down	down	down	

The elaborate switching system shown in Fig. 3 is not necessary for simple current measurements, but was installed for flexibility in the use of the same equipment for other related tests.

B. *Apparatus.*

C_s is a guard-ring condenser arranged to provide a uniform dielectric field between the parallel surfaces of the specimen and to allow the measurement of the current passing to the middle plate. It is mounted so that potential can be applied to the lower plate.

Q. E. is a Compton quadrant electrometer with a platinum sputtered quartz fiber. A potential of about 60 volts has been maintained on the needle for several months. The adjustment is such as to give a sensitivity of from 3000 to 4500 mm./volt, the scale being mounted at two meters. Sensitivities as high as 15,000 mm./volt were obtained but they were accompanied by rather unstable conditions with large shifts of the electrometer zero and were therefore not used. The instrument is

shielded from air currents and the case is permanently grounded.

C_A is an air condenser of known capacitance. A 64 by 10^{-12} farad fixed condenser having long quartz rods supporting and insulating one set of plates was used for measurement of the smallest currents. A variable parallel-plate air condenser, having a range in capacitance from 76 by 10^{-12} to 5360 by 10^{-12} farad, was used for measurement of larger currents. For these experiments, this capacitance was used at only three settings, namely, 5360, 1000, and 100. The rotating set of plates was mounted on amber bushings so as to eliminate leakage currents so far as possible.

P is a Queen-Gray potentiometer carrying a normal current of 0.002 ampere with a potential range from zero to 1.91 volts, the smallest graduated division being 0.00001 volt. For large current readings, the potentiometer current was increased ten times, thus multiplying the potential readings by ten.

A is a milliammeter for roughly measuring the current in P. Final adjustments were made by checking against a standard cell. The potentiometer current was kept flowing continuously, so as to maintain constant temperature, and therefore constant resistance, in the coils.

V is a voltmeter for measuring either the potential to be applied to the specimen or that on the electrometer needle.

G is the common grounding point for the entire system.

B_1 supplies constant potential to the electrometer needle.

B_2 is a battery of over 800 volts for supplying any desired potential to C_s.

B_3 is a 24-volt storage battery supplying the continuous current in P.

C. Preparation of Specimens.

With Air-Gap. The first series of experiments was made with specimens having polished plane parallel surfaces placed between the plates of a standard air condenser. The upper plate consists of two parts, the center section and a guard-ring. The guard-ring is supported on amber bushings which insulate it from the lower plate. The height of these bushings may be adjusted to give any desired spacing between the plates up to about an inch. The center section is supported from a brass cross-bar which is insulated from the guard-ring by a pair of sulphur bushings. The guard-ring was permanently grounded and the center section, although isolated from ground during a reading, was maintained at ground potential. (See method of making measurements.) Thus, a uniform electric field was maintained in the specimen out to the edge of the guard-ring and fringing was eliminated at the edge of the center section on which measurements were made.

A copper wire, supporting one of the glass mercury cups, was mounted on the isolated center section of the upper plate. A mechanical lever arrangement was provided so that the entire condenser could be rocked, thus moving the mercury cup up and down. An amalgamated copper wire suspended directly from the electrometer quadrants was adjusted to dip in this mercury cup when the latter was in its up position, but to be several millimeters above the surface of the mercury when the cup was down. Thus the connection between C_s and $Q. E.$ could easily be made or broken, being remotely controlled from the observer's position behind the electrometer scale.

In the piece of apparatus just described, no attempt was made to provide good electrical contact between the lower surface of the specimen and the brass plate upon which it rested. A small air-gap here due to irregularities in the surface could be considered as part of the total air-gap, since there was from 1 to 2 mm. space between the upper surface of the specimen and the upper plate of C_s.

With Intimate Contact. Later, we wished to eliminate entirely these air spaces and several methods were suggested for providing electrical contact between the condenser plates and the surfaces of the specimen. We were prejudiced against the use of mercury contacts by the difficulty of making a suitable guard-ring arrangement, and also by the work of J. E. Shrader[9], who concluded from his experiments that powdered graphite provides better contact than mercury, especially on polished surfaces. We finally decided on two methods of making these contacts: (a) by depositing a metal film on the surface, either by silvering or by sputtering in vacuum, or (b), by painting both the specimen and condenser plate surfaces with India ink in which we had mixed very finely powdered graphite and sticking them together while wet. When dry, they adhere to each other and the India ink with graphite provides a conducting surface on the face of the specimen.

In either of the above methods, it is imperative that the area of the specimen surface between the center section of the upper plate and the guard-ring be perfectly clean and free from any conducting material. For this reason, considerable care must be taken in mounting the brass plates.

D. Experimental Procedure.

Detailed Procedure. Before starting a run, to insure that the specimen had no residual polarization, the switches were thrown as shown under A, Table I, Under this condition, C_s, $Q. E.$, and C_A were connected together and isolated from the rest of the set-up, all of which was grounded. If the specimen had any residual polarization, the electrometer would show a drift in one direction or the other; but if the sample were completely depolarized, there would be no electrometer drift, in which case the specimen was ready for test. If the electrometer showed a drift, both plates of the condenser containing the specimen were grounded and left until the residual polarization became zero.

Before starting the experiment, it was also necessary

to adjust the potential of B_2 to exactly the value required to give the desired potential gradient in the specimen. The voltmeter V was used in making this adjustment.

For aid in describing the exact method of procedure, let us consider the sample data sheet shown in Table II.

At exactly 8:00 p. m., potential was applied to the specimen by throwing switch 9 to the right, switch 1 having been previously closed and switch 8 opened. The charging current was then passing through switch 1 to ground without being measured. The position of all switches is shown in column B, Table I.

TABLE II
SAMPLE DATA SHEET
L. N. hard rubber at a potential gradient of 400 volts/cm.

April 2, 1927 Sample 5 with India ink contacts, C_A = 1000

Time	Minutes	*Q. E.* Zero	*P* Volts	*e* Volts	*ix* 10^{-15} Amps.
8:00:00 p.m.	0	70.25	(Applied potential B_2 = + 246.5 volts)		
0:45			0		
1:15	1		−0.04	−0.04	+1333
1:45			0		
2:15	2		0.0245	0.0245	816.6
3:30			0.0025		
4:30	4		0.027	0.0245	408.3
5:30			0.00145		
6:30	6		0.01825	0.0168	280.
7:30			0		
8:30	8		0.01305	0.01305	217.5
9:30		69.6			
10:00			0.00115		
13:30		69.3 Est.*			
14:00	12		0.0381	−0.03695	155.2
14:30		69.15		−0.0003	
15:00			0.00305		
18:30		68.7 Est.*			
19:00	17		0.0305	0.02745	114.4
19:30		68.75			
4/4/27 a.m.					
11:00:00		64.9	(Removed Potential)		
0:45			0		
1:16	1		+0.04	+0.04	−1290
1:45			0		
2:15	2		0.023	0.023	766.7
3:30			0.003		
4:30	4		0.0259	0.0229	381.7
5:30			0.0025		
6:30	6		(missed the reading)		
7:30			0.00295		
8:30	8		0.01505	0.0121	201.7
9:30		64.05			
10:00			0.0045		
13:30		63.6 Est.*			
14:00	12		0.0367	+0.0322	132.5
14:30		63.75		−0.0004	
15:00			0.00363		
18:30		63.35 Est.*			
19:00	17		0.02695	+0.02332	96.33
19:30		63.45		−0.0002	

*Estimated.

Exactly 45 sec. later, switch 1 was opened and P was continuously adjusted so as to keep the electrometer spot of light approximately at its zero position. P was carefully adjusted so that the electrometer spot was *exactly* on its estimated zero position at 8:01:15, after which, switch 1 was again closed and the reading of P recorded. The potentiometer slider was then set back to zero ready for the next reading. This process was repeated whenever it was desired to take a reading. At the end of each reading, in fact 30 sec. after closing switch 1, the true position of the electrometer zero was read. If this differed from the estimated position, the reading was corrected for the error, the electrometer calibration having been previously determined. The readings came in rapid succession, at least for the first few hours, after which they could be taken at longer intervals.

Eliminating Switching Errors. The electrometer zero position was not stationary, but was continually shifting. Therefore it seemed necessary, especially for readings of 10 min. duration, to provide a switching arrangement so that the electrometer zero could be accurately determined just before the final adjustment was made at the end of a reading. For this purpose, a mercury cup was provided, into which an amalgamated copper wire could be made to dip. (Switch 3.) When it was desired to determine the electrometer zero without grounding the combination of C_s and C_A, switch 3 was opened, switch 1 closed, and the zero position read on the scale. Then switch 1 was opened, switch 3 closed, and the final adjustment of P made to bring the spot of light to its zero position.

There were two possible sources of error in this process.

a. If, when switch 3 was opened, the isolated system was not at ground potential, a certain amount of electricity was removed from the system when the electrometer was grounded. For readings at the very end of a discharge curve, this quantity might be an appreciable proportion of the total charge collected during the 10-min. period.

b. The second source of error was probably the greater, however. It seemed impossible to keep the mercury sufficiently clean to eliminate a contact e. m. f., which was generated every time a switch was opened or closed. It was suggested that a layer of oil might be placed on the mercury to eliminate oxidation and thus prevent this e. m. f. This was not tried, however, because the method already described was devised for taking the data without making any switching operations during a reading.

Minimizing Leakage Errors. The value of current to be measured was so small that extra precautions had to be taken to make sure that electricity did not leak on to the system from some outside source, or that current which we wished to measure, did not leak off without being measured. For these reasons, the entire outfit was surrounded with a permanently grounded electrostatic shield. Also, the set-up was so designed that the isolated system, comprising the upper plate of C_s, the electrometer quadrants and one set of plates of C_A, was supported entirely by these three pieces of apparatus. Thus, the four chances for leakage from this system were:

1. Surface leakage from the upper plate of C_s to the guard ring;

2. Surface leakage from the free quadrants of *Q. E.* to its case;

3. Surface leakage over the insulating supports, from one set of plates to the other of C_A;

4. Conduction through the air due to ionization.

To guard against the first, the surface of the hard rubber was carefully scraped before the guard-ring and upper plate were mounted, the surfaces of the glasses were cleaned with concentrated nitric acid, washed with ammonium hydroxide, and then with distilled water.

The second possibility offers very little chance for leakage since the quadrants were mounted on amber, the surface of which had been highly polished and carefully cleaned.

The third offers a greater chance for leakage. The larger condenser C_A is of the multiple-plate type manufactured for precision radio work. The insulation furnished by the manufacturer was a pressed mica composition. This was found to have relatively large surface leakage and was replaced by Bakelite strips having amber bushings. Even with these precautions, it was found that the combination of the electrometer with C_A, C_s being disconnected, showed a leakage drift always in the same direction but varying erratically from 2 by 10^{-15} to 10 by 10^{-15} amperes. In an attempt to decrease this leakage when reading small currents, a small fixed air condenser was made with one set of plates insulated and supported by long quartz

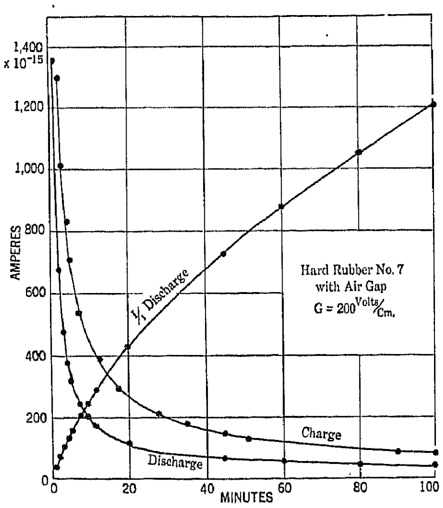


Fig. 4—Hard Rubber No. 7 With Air-Gap

rods. The system leak was thereby reduced to about one-third the previous value.

The fact that the observed leakage was always in the same direction leads us to think that some at least was due to the fourth possibility mentioned above, especially in C_A where the air path between plates was relatively short and of large area.

J. J. Thomson[13], in his book "The Conductivity of Electricity Through Gases", quotes C. T. R. Wilson, who, in 1901, showed that in dust-free air, the maximum quantity of electricity which can escape in one second from a charged body in a closed space whose volume is V cu. cm. is about $10^{-8}\ V$ electrostatic units. This equals about 0.333 by $10^{-17}\ V$ coulombs per sec., and is sufficient to account for part, but probably not all, of the leakage observed in our experiments.

Null Method Eliminates Electrometer Errors. The errors that make it inconvenient to use an electrometer as a deflection instrument will be summarized briefly.

It is difficult to determine accurately the capacitance of C_s or the electrometer, and both of these must be

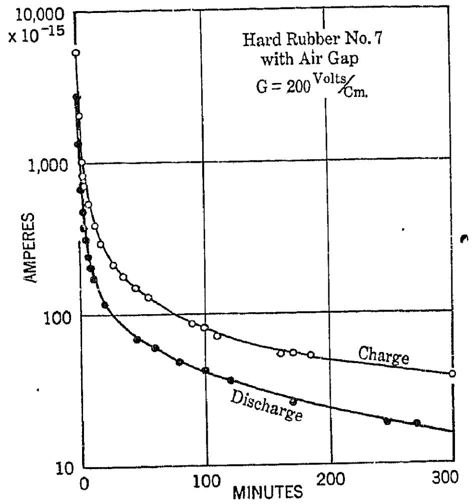


Fig. 5—Hard Rubber No. 7 With Air-Gap

known if the deflections are to be interpreted in amperes. The electrometer capacitance changes with any change in the position of the needle. The fast readings are in error because of the inertia of the moving needle and the viscosity of the air surrounding it. More serious than any of these, perhaps, is the fact that the calibration changes with variations of the zero position and other factors; and also that there is not a straight line relation between deflection and the potential on the quadrant.

For all of these reasons, while an electrometer is very useful in making relative measurements, it has disadvantages when used as a quantitative instrument. Therefore, the simpler quantitative method already described was devised, using the electrometer only as a very sensitive zero potential indicator.

Experimental Results

A. *With Air-Gap.*

As already indicated, the first tests were made with the gap between the upper surface of the specimen and the upper plate of the condenser. A plate of hard rubber and one of Pyrex glass were tested in this way.

In Fig. 4, curve 1 shows the charge curve which although not plotted, was continued for nearly 4000 min., or until the current had decreased to about 15 by 10^{-15} amperes. Curve 2 shows the discharge taken

after the charge by removing the potential and grounding the lower plate.

Fig. 4 is shown for two reasons: first, to illustrate how rapidly the current drops during the first part of the discharge curve, and yet how long, relatively, it takes for this current to die out entirely. The second reason is embodied in curve 3, in which the reciprocals of the points on curve 2 have been plotted against time. If curve 2 were an hyperbola with the axes for asymptotes, curve 3 would be a straight line passing through the

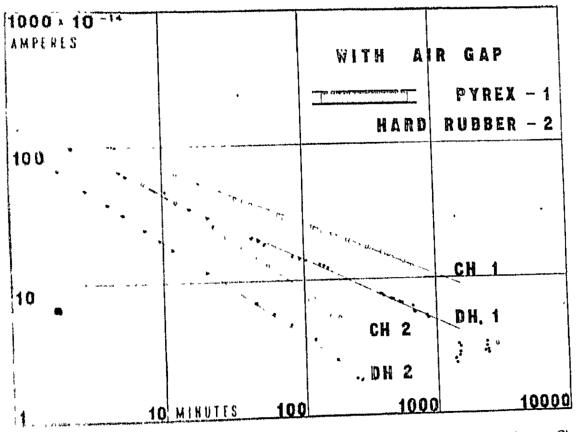


Fig. 6—Hard Rubber No. 7 and Pyrex with Air-Gap

origin. The plot shows very definitely that curve 2 is not a hyperbola.

The wide difference between curve 1 and 2 is due to the air-gap, for eliminating the gap eliminated the difference, except for the actual conduction current which is, of course, absent on discharge, (see Figs. 7 and 8). For this reason, subsequent tests were made with intimate contact between the specimen and upper plate of C_a.

Fig. 5 shows that the relation between i and t does not even approximately follow a simple exponential law.

The charge and discharge curves for hard rubber, which have been shown in the last two figures plotted in different ways, are plotted in Fig. 6 using logarithmic scales for both current and time ($C\,H-2$ and $D\,H-2$). It is seen that the experimental data give practically a straight line relationship between log. i and log. t.

$C\,H-1$ and $D\,H-1$ are similar charge and discharge curves taken for a sample of Pyrex glass, nearly 15 cm. thick. The principal fact to be gained from these is that the straight relationship makes the polarization an inverse power function of the time:

$$i_p = (\text{const})\, t^{-b} \qquad (2)$$

B. With Intimate Contact.

Pyrex Glass. After the curves and $C\,H-1$ and $D\,H-1$, shown in Fig. 6, had been obtained, the same specimen was prepared with intimate contact between the surfaces of the specimen and the plates of the condenser. The results of this latter test, plotted in a similar manner, are shown in Fig. 7.

The upper series of circles, through which no line is drawn, are points on the charge curve which is approaching a horizontal asymptote, the final conduction current I_g. In the case of Pyrex, I_g is a very appreciable proportion of the charge current.

The series of completely filled dots gives the observed discharge curve, which follows the straight-line law for over 100 min., after which it drops off more rapidly.

The series of half filled circles is obtained by subtracting the value I_g from each of the charge readings, obtaining thereby the effect of polarization alone. These lie superimposed upon the points of the discharge curve showing that the phenomenon is reversible. This relationship may be expressed by the equation:

$$i_p = i\ (\text{charge}) - I_g = -\, i\ (\text{discharge}) \qquad (3)$$

This relation was stated long ago by Curie[4] as a result of the law of superposition.

Although charge curves similar to Fig. 7 are not shown in his published work, the relation represented by eq. (2) was reported by von Schweidler,[10] who obtained discharge curves, similar to those shown in Fig. 7, for mica, paraffin paper, and glass condensers.

A curve for fused quartz obeying the law of eq. (2), was shown by A. Jaquerod and H. Mugeli;[5] but they, like von Schweidler, chose to convert this simple experimentally observed relation to a sum of exponential terms, believing this form easier of theoretical explanation.

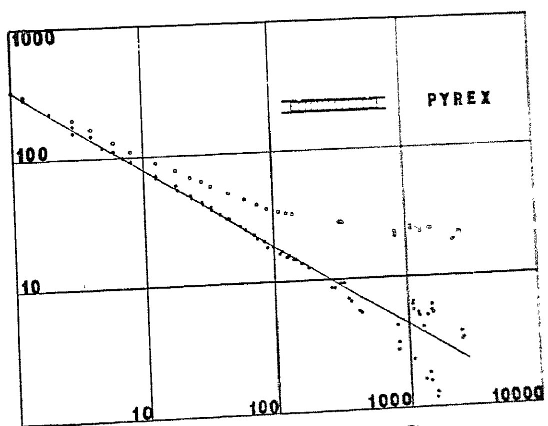


Fig. 7—Pyrex with Intimate Contact

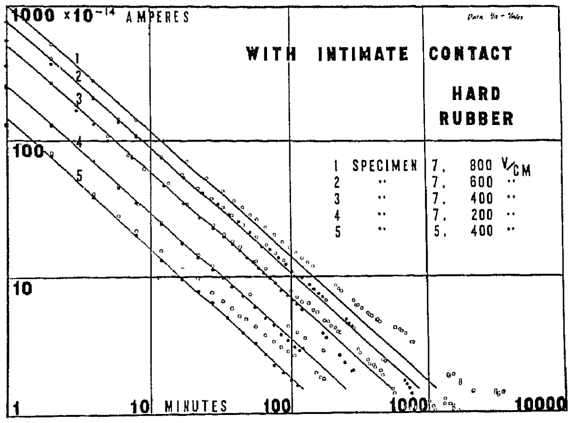
The deviation of observed points in Fig. 7 from the straight-line law may be due to one or both of two causes.

a. A slightly erratic unidirectional instrument leak, comparable to the lower values of the curve, was observed. This error decreased the discharge readings but added to the charge readings, the charge current being in the opposite direction to the discharge. The error might well account for the observed departures for the points of $i_{CH} - I_g$ lie above the line and the discharge points lie below it.

b. The other possible explanation is that the reaction

of the material actually does not obey the law. This can be determined only by further experiment using more refined methods so as to eliminate possible apparatus errors.

Hard Rubber. Fig. 8 shows the results of a series of experiments on two samples of hard rubber. Specimen 7 was tested at four different potential gradients, giving curves 1, 2, 3, and 4. Specimen 5, obtained from



IG. 8—HARD RUBBER NO. 5 AND NO. 7 WITH INTIMATE CONTACT

a different manufacturer, was tested at only one potential gradient as shown by curve 5. Curves 1, 3, and 4 were taken with a positive potential applied to the lower plate of the condenser. A poor switch contact destroyed the value of the discharge readings for curve 1, so that they were not plotted. Curve 2 was taken with a negative potential applied to the lower plate of the condenser. This shows that the results were independent of the direction of the applied potential.

The unidirectional apparatus errors were found by several tests to be comparable to the value of the final conduction current for hard rubber. In runs 1, 3, and 4, these errors were in the same direction as the final conduction current and therefore add up to give the observed constant value I_g. In run 2, the apparatus errors were in the opposite direction to the conduction current, and therefore lowered the charge and raised the discharge curve. Indeed it seems that the errors and the conduction current are about of the same magnitude, for the charge and discharge curves are nearly superimposed. This suggests a way of canceling out the errors, if it is found impossible to remove their cause; namely, to take two runs at each potential gradient under identical conditions, except that the direction of the potential is reversed.

Because the experimental data indicated that the curves were directly proportional to the applied potential, the lines 1, 2, 3, and 4, were so drawn. They are plotted parallel and apart by distances, so that the ordinates of current at any instant are directly proportional to the applied potential gradient. By observing the agreement of the lines with the observed points, the reader may draw his own conclusions regarding this proportionality.

Curve 5 shows that specimen 5, while having approximately the same time rate of change of polarization as specimen 7, gives less than one-third as much polarization under the same conditions. The composition of these two samples is not known to the writer, so no deduction can be made as to the reason for this difference.

The values of I_g, taken at the end of each charge curve, included the apparatus errors in the same direction as the actual conduction current. Therefore, the best we can say is that the actual conduction current was equal to, or less than, the observed value; and that the actual apparent resistivity of the material was equal to or greater than that computed using the observed values of I_g. (See Table IV.)

Fused Quartz. A sample of fused quartz and one of crystalline quartz on which some previous measurements had been made were obtained from the Bureau of Standards. The writer believes that these are the same samples used by V. E. Whitman[16] in making similar studies on current flow in fused and crystalline quartz. The fused quartz was in the shape of a thin disk with plane parallel faces. It was silver-plated on both sides, with a suitable guard-ring.

Fig. 9 shows a typical example of some of the first measurements made on this sample. No measurements were taken within the first minute after applying or removing the potential and it is impossible to show exactly what was happening at the two extremes of either curve since in this figure they were plotted to uniform scales.

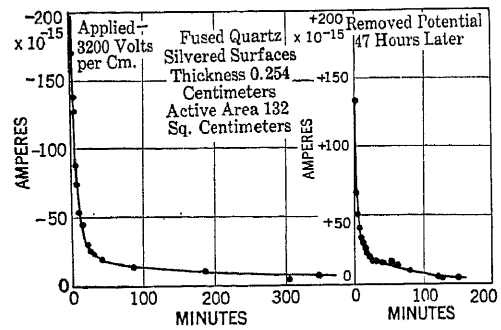


FIG. 9—FUSED QUARTZ WITH SILVERED SURFACES

Several sets of data with different applied potentials were taken with the hope of finding the relation previously shown for hard rubber in Fig. 8. No such relation was found; on the contrary, it was impossible to get the same curve twice with the same applied potential. Also curves obtained with positive applied potential, while of the same form, were not symmetrical with those obtained with a negative applied potential. In fact, the current-time curves for this sample did not seem to obey any quantitative law, but seemed rather to be unaccountably erratic.

It might be well to state here that the upper plate of

C_s (see Figs. 2 and 3) was connected to ground all of the time except while a reading was actually being taken; even then, it was kept at ground potential. Each time before potential was applied the sample was tested to be sure that there was no residual current flowing due to relaxation from some previous charge.

The investigator was gradually convinced that something unexpected, and which he was not observing,

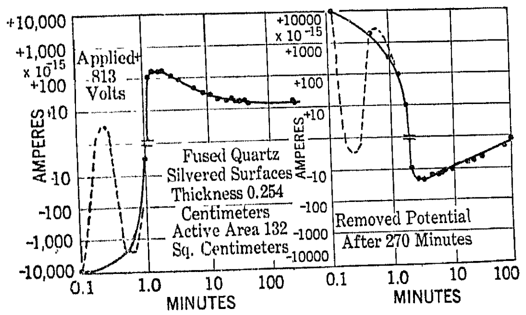


Fig. 10—Fused Quartz with Silvered Surfaces

was happening during the first minute. Up to this time the first reading for each curve had been taken one min. after applying or removing the potential. Thereafter, the electrometer was used quantitatively, and as many readings as possible obtained during the first minute.

Fig. 10 represents a typical set of results, the heavy line showing how they were first interpreted. These points give no indication of the current flow between the relatively short observations; and subsequent curves indicated that the data should be interpreted as slow oscillations shown by the dotted curve.

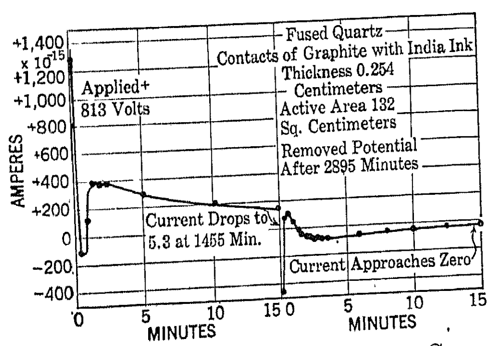


Fig. 11—Fused Quartz with Graphite Contacts

At first it was suspected that this reversal might be caused by some peculiar condition of resonance in the circuit. This idea was discarded because when an air core inductance of about 400 millihenrys was connected in series with C_s, no apparent change was noticed in the charge and discharge curves. Computations also showed that impossible values of circuit constants would be necessary to give a frequency of natural oscillation as low as one cycle per min. Therefore it was concluded that these reversals were either due to the contact surfaces, or else were a characteristic of the material itself.

The next step was to try new contact surfaces. The silver film was removed from the quartz plate, the surfaces were carefully cleaned, and new contacts provided by painting with India ink containing finely powdered graphite. The first coat was allowed to dry; then a brass disk was painted with the same mixture and placed on the coated surface, thus insuring good contact, since the brass was held firmly after the ink had dried.

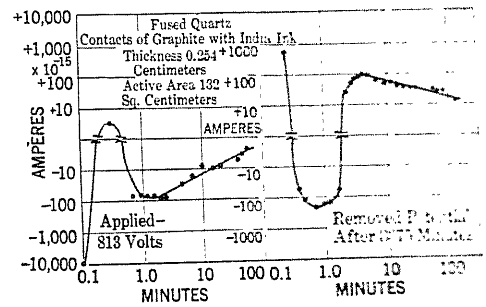


Fig. 12—Fused Quartz with Graphite Contacts

Figs. 11, 12, and 13 show typical sets of data taken with the new contacts. The reversals are shown very clearly. The relative magnitudes of the first and subsequent readings for each run are indicated best by Fig. 11, which is plotted using uniform scales. The same set of data is plotted for a much longer time in Fig. 12, using logarithmic scales. The effect of applying a negative instead of positive potential to C_s is shown in Fig. 13.

In Figs. 12 and 13 the curves are broken where they

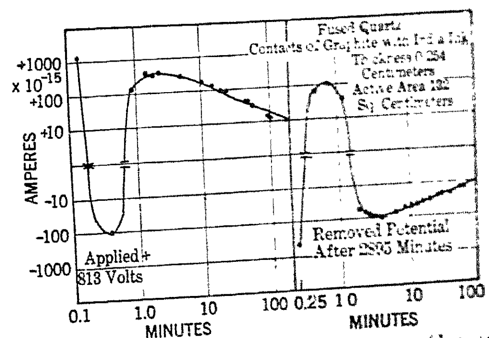


Fig. 13—Fused Quartz with Graphite Contacts

cross the axis because the scales are logarithmic and no zero can be shown. So far as we could see, changing the contact surfaces did not affect the results, so that they indicate the reactions of the material itself. It is quite possible that in each case the observed results were preceded by unmeasured oscillations of much shorter period. As an aid in the possible interpretation of these results, the complete history of this sample of fused quartz, for two months preceding the final experiments, is tabulated in Table III.

TABLE III

HISTORY OF PLATE OF FUSED QUARTZ

Previous to the tests recorded below the plate, with silvered surfaces connected together had been lying idle for some time. No residual charge could be detected

Date	Days after 11/20	Treatment	Remarks
11/20/27	0	Applied − 813 volts	Data plotted Fig. 9
11/22	2.1	Removed potential	
11/24	3.96	Applied + 813 volts	Suspected erratic behavior at beginning
11/25	4.98	Removed potential	
12/6	15.96	Applied − 406.5 volts	Observed reversal during first minute
	16.17	Removed potential	
12/7	17.1	Applied + 406.5 volts	Observed reversal during first minute
	17.35	Removed potential	
12/8	18.13	Applied − 813 volts	Reversal observed but ordinates were not proportional to potential applied
	18.35	Removed potential	
12/13	22.92	Applied + 813 volts	Observed reversal
12/14	24.12	Removed potential	No data
	25.18	Applied − 813 volts with 376 millihenrys in series	No apparent effect in results
12/15	25.22	Removed potential	
12/16	26.33	Applied + 813 volts with same inductance in series	No effect
12/17	26.92	Removed potential	
	27.08	Applied + 813 volts without series inductance	
12/17	27.12	Removed potential	No effect
1/ 9/28		Applied + 813 volts after plate had been grounded for three weeks	Data plotted Fig. 10
	50.19	Removed potential	
1/14	55	Silver surfaces were removed and India ink with graphite contacts provided	
1/18	59.1	Applied + 813 volts	
1/20	61.12	Removed potential	Data plotted
1/21	61.96	Applied − 813 volts	Figures 11, 12, and 13
1/23	64.3	Removed potential	

Reversals of Current in Fused Quartz.

Reversals in direction of discharge current curves occurring after corresponding reversals of the charging potential have been observed by numerous investigators.[6] Richardson[8] shows curves demonstrating this effect for a sample of crystalline quartz cut parallel to the axis. The law governing the effect was stated in 1889 by Jacques Curie[1] as the principle of superposition.

However, the results shown in Fig. 10 to 13 cannot be explained by this principle because the specimen is kept grounded (short-circuited) after each test until it has relaxed as completely as it will; *i. e.*, until the upper plate shows no tendency to acquire a charge in either direction if the ground connection is removed. This is assumed to indicate a neutral or unstressed condition in the dielectric. Then, according to the principle of superposition, if a positive potential of constant magnitude were applied, the current flow would always be in the positive direction.

Perhaps, upon depolarization, the polarizing elements do not regain truly neutral positions, although they do assume an arrangement which is in stable equilibrium. Thus, the reversals observed might be caused by overstraining and slow time oscillation about a new equilibrium arrangement whenever the applied potential is changed.

This effect might be accounted for by the condition assumed at the point (6) of Fig. 12 in the recent paper published by Malti[7].

The writer is not prepared to offer any other explanation of the results observed, although he believes them to represent truly the reactions of the sample tested. He would be very pleased to learn whether other investigators have observed similar reactions on fused quartz or other materials.

TABLE IV

SUMMARY OF EXPERIMENTAL RESULTS

All data were taken at temperature of 20 deg.–22 deg. cent.

1	2	3	4	5	6
Hard rubber .... No. 7.........	200, 400 600, 800	6.5 by 10^{15}	3.6 by 10^{18}	550/1	0.924
Hard rubber .... No. 5.........	400	1.7 by 10^{16}	3.2 by 10^{18}	190/1	0.953
Pyrex glass...... No. 12........	200	4.9 by 10^{15}	8.6 by 10^{16}	17.5/1	0.6262
Fused quartz.... No. 14........	3200	1 by 10^{18} approx.	8 by 10^{19}	80/1	0.678
Crystalline quartz No. 11.	1000	1 by 10^{16}	1 by 10^{16}	1/1	0.525

Column 1—material under test

Column 2—G = applied potential gradient in volts/cm.

Column 3—$\rho_a = \frac{e}{i_1}$ = apparent resistivity where i_1 is the current per unit area in amperes/sq. cm. measured 1 min. after the application of potential

Column 4—$\rho_f = \frac{e}{i_g}$ where i_1 was the final constant value of i

Column 5—ratio of ρ_a/ρ_f

Column 6—coefficient b, when the polarization current is exressed by equation (1).

A compilation of the known characteristics of silica is presented by Sosman[12], "The Properties of Silica." However, no information similar to that observed by the writer was found in this work.

Crystalline Quartz cut Parallel to the Axis. A plate of clear crystalline quartz, cut parallel to the axis, was also borrowed from the Bureau of Standards. The contacts on this sample were made by sputtering a gold film in vacuum on the carefully cleaned surfaces. Here, again, a guard-ring was provided. The chief objection to this type of contact is the length of time necessary to get a good conducting film.

Fig. 14 shows the only set of data obtained to date on this sample. The upper curve shows that the final steady current is very high compared to that of fused quartz. The lower curve shows a return polarization current larger than the charging current for the first minute and a half, and continuing for an extremely long time. In fact, one month after the potential was removed, a discharge current could still be detected, although the

plates had been short-circuited for the entire time. This indicates the difficulty of obtaining complete relaxation in such a material. The writer believes that if the charging current had been continued for 100,000 min., the lower part of the discharge curve might have continued a straight line instead of falling off as it did.

Suggestions for Further Research

A. Studies Similar to Those Reported Here.

1. Studies on a large number of materials to separate them into the following three groups; (a) those showing both polarization and conduction; (b) those showing appreciable polarization and negligible conduction; (c) those showing negligible polarization and appreciable conduction.

For these studies, it would be necessary to keep constant the parameters listed below; but this would not require the apparatus necessary to vary them through wide limits, and therefore could be done much more easily.

2. Intensive study on a representative substance from each of the three groups listed above. To accomplish such a study, it would be necessary to control all of the variables which affect the phenomena. Then,

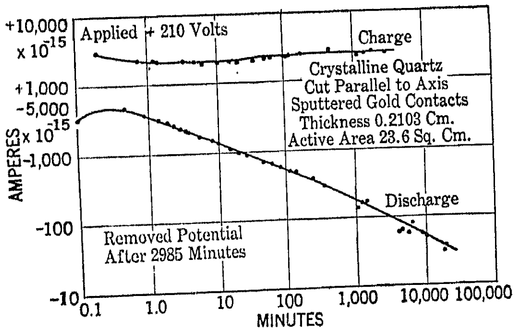


Fig. 14—Crystalline Quartz with Gold Contacts

by varying one at a time, keeping all the others constant, the individual effects of each parameter could be studied. This would be a large undertaking, require especially designed apparatus, and take a great deal of time. However, we cannot say much regarding dielectric reactions until it is accomplished. The possible parameters are: (a) thickness of specimen; (b) area of specimen; (c) temperature; (d) humidity; (e) potential gradient; (f) length of time of application of potential.

From this study a classification would be obtained separating dielectrics into two groups: (a) those whose reactions obey laws of proportionality with the possible parameters, and whose reactions can therefore be computed; (b) those whose reactions are quantitatively erratic and non-predictable.

B. Studies of Polarization Potential.

The author believes that very interesting current-time relations will be found if, after a complete charge curve, the potential is reduced, not to zero as in the case of all the tests reported in this paper, but to a potential smaller than that previously applied and in the same direction. A family of such curves could be obtained by having identical charging conditions, and reducing the potential to different values, ranging from zero up to the potential applied during charge, (see Reference 8).

C. Studies of Residual Charge.

If, after a complete charge curve, the condenser is short-circuited and then isolated, a difference of potential will gradually appear between the plates, showing that a free charge is collected on them which may be removed by again short-circuiting the plates. It would be very interesting to study this liberation of residual charge:

1. As a function of the time allowed between successive short circuits;

2. As a function of the rate of rise of potential which could be controlled by varying the capacitance of an air condenser placed in parallel with the specimen.

D. Studies of Energy Involved.

1. Input Energy.

This may be computed by the equation

$$W_{input} = E_{CH} \int_{o}^{d} i_{CH}\, d\, t \qquad (4)$$

where d is the time at which the charge is discontinued.

2. Recoverable Energy.

If experiments are performed as indicated under section B, above, and the value of the reduced potential E_{DH} is such that current flows against this potential, the energy recovered is given by the equation:

$$W_{recovered} = E_{DH} \int_{o}^{f} i_{DH}\, d\, t \qquad (5)$$

where f is the instant of time at which i_{DH} reverses and begins to flow in the same direction as the previous charge current.

3. Loss to Heat.

The difference between the energy input and the energy recovered is energy lost. In all the experiments reported in this paper, the energy recovered was zero, since both plates of the condenser were maintained at zero potential during discharge. Therefore, all the energy input was lost to heat; (a), in forcing the material through the cycle of polarization, and (b), in the actual $I_g^2\, r$ loss. Therefore, the energy used in polarization could be computed by substracting from the input energy, the energy recovered, and the $I_g^2\, r$ loss, if we could assume that I final $= I_g$.

E. Correlation of A-C. and D-C. Tests.

As the frequency of the alternating potential is decreased, the loss per cycle ought to approach the loss per cycle of a d-c. test having the same magnitude of applied potential. Therefore, very interesting data should be obtained by using the same sample for both types of experiment and comparing the results.

Summary

A. A simple, sensitive modification of previous methods is developed for measuring current-time,

charge and discharge curves in solid dielectrics with constant applied potential.

B. Coefficients of final apparent resistivity agree very well with those reported by earlier investigators. The fact that a higher value is reported for fused quartz is due to the extreme length of time taken, to allow the current to decrease to its minimum, and to the high sensitivity of the method of measurement.

C. The phenomenon studied must be due to some form of polarization, since representative curves were obtained with an insulating air-gap between the specimen and the upper plate of C_s.

D. 1. For all the materials studied, the law expressed by equation (2) is verified over a considerable length of time. An exception was found in fused quartz during the first minute or so after changing the applied potential.

2. The law expressed by equation (3) is verified for Pyrex glass and hard rubber.

3. For hard rubber within the range of potential studied, we have found that the polarization current is directly proportional to the applied potential, and that the relaxation coefficient b in eq. (2) is independent of the applied potential.

4. The sample of fused quartz behaved differently from the other materials tested, and showed current reversals unaccounted for by the principle of superposition. Its reactions cannot be taken as representative of all dielectrics.

E. The final apparent resistivity of some materials can be determined only after a constant potential has been applied for several days; *i. e.*, it takes days, and even weeks, for i_p to become negligible compared to I_g.

F. Of the several methods tried, India ink with finely powdered graphite was found to give the most satisfactory contact between the surfaces of the specimen and the brass plates of C_s.

General Conclusions

A. Solid dielectrics showing the property of polarization may be found to divide themselves into distinct groups having entirely different conduction characteristics.

B. The mechanism of conduction in dielectrics differs from that in metals so that the expression "dielectric resistance" has an entirely different physical meaning from the expression "metallic resistance."

C. The present need in this field is for thoroughly coordinated, carefully executed researches to determine how *all* the related phenomena vary with changes of *all* the parameters which affect them.

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Extended biliographies on this subject will be found in references 6, 7, 10, 14, and 15. The others listed are simply those to which direct reference has been made in this paper.

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Discussion

C. L. Dawes: I am particularly interested in work which involves the properties of dielectrics, since at Harvard University we are and have been for some time past conducting a similar study. In fact, P. L. Humphries, an instructor in Electrical Engineering, has already obtained the dielectric characteristics

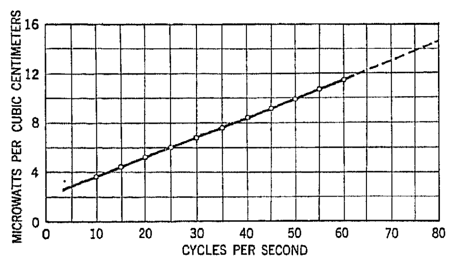

Fig. 1—Frequency-Power Characteristic of Pyrex

3450 volts per cu. cm. gradient. Temperature—25 deg. cent.

of Pyrex glass over a wide range of frequencies and temperatures. These results will be published in the *Electrical World* in the near future. Our special problem at present is the study of the ionization of gases. We restrict the energy flow to the gas with a slab of Pyrex glass, having an effective electrode area of 111.3 sq. cm. and a thickness of 1.411 cm. The characteristics of the gas are obtained by deducting the characteristics of the Pyrex glass from the measured characteristics of the glass and gas in series. It is, therefore, necessary to know the characteristics of the Pyrex glass. We first used ordinary plate glass, but later found Pyrex glass more suitable, because its characteristics vary much less with change in temperature. We attempted, without success, to obtain a suitable piece of fused quartz for this work.

In Fig. 1 herewith is shown a plot which gives the power loss of Pyrex glass as a function of frequency. The curve was obtained at 25 deg. cent. and with 5000 volts r. m. s. impressed, giving a gradient of 3540 volts per cm. The relation of power loss to frequency is linear. If the curve is extrapolated to zero frequency, the corresponding loss is 1.4 microwatts per cu. cm. This corresponds to 4.47×10^{-9} watt per cu. cm. if the voltage gradient is 200 volts per cm. The watts loss per cu. cm. obtained by Professor Race with a gradient of 200 volts per cm. and at the final constant value of direct current may be obtained from Table IV and is equal to $(200)^2/(8.6 \times 10^{-16}) = 4.65 \times 10^{-13}$ watt. It is thus seen that there is a great difference between these two values. It does not seem possible that this difference can be accounted for by differences in the specimens tested.

It would have added considerably to our knowledge of dielectrics if it had been possible for us to obtain data between 20 cycles per second and zero frequency, and thus attempt to explain the above discrepancy. Addenbrooke[1] has made some comparisons of the d-c. characteristics of dielectrics with their a-c. characteristics. However, in our present research we are not particularly concerned with the Pyrex glass itself, but rather in the application of its dielectric characteristics to another problem. Hence, at this time we do not feel justified in carrying the research any further in this particular direction.

At first sight, it seems an anomaly that in the measurement of power loss, we are able to obtain far greater sensitivity with alternating current than with direct current, in spite of the fact that with alternating current, the energy component of the current is associated with a quadrature component having many times the value of the energy component. These two components must be separated in the power measurement. The reason that this high sensitivity is obtained with alternating current is that we are able to employ a very sensitive tuned galvanometer, working in conjunction with a vacuum-tube amplifier. Although we have an extremely sensitive d-c. galvanometer (10^{-11} ampere for 1 mm. deflection at a distance of one meter) its sensitivity would need to be increased 1000 times to adapt it to the measurements of these samples of high-resistivity materials. Hence, some indirect method, such as is described in Professor Race's paper, is usually necessary Heretofore, very small currents such as electronic saturation currents, have been determined by measuring the change of potential across a condenser with some type of electrostatic instrument, often a gold-leaf electroscope. Professor Race eliminates the deflection errors, which are large in this type of instrument, by means of an electrostatic Poggendorff method. The instrument acts merely as a zero detector. From my own experience with this type of measurement, I agree with him that this null method has much greater inherent precision than the deflection method.

It is interesting to note that d- and a-c. losses in cables have been compared by Percy Dunsheath of the Henley Telegraph Works of England. He has found that for the same voltage gradient, the a-c. loss at 50 cycles varies from 13.4 to 3460 times the d-c. loss, depending on the temperature. ("Dielectric Problems in High-voltage Cables;" *Journal I. E. E.*, Vol. 64, 1925-26, page 113). At Harvard University we are making similar studies with cables and plan to publish some of the results.

We all realize that our present knowledge of the behavior of dielectrics is rather vague. The Committee on Dielectrics of the National Research Council and various committees of the national engineering societies are working to avoid unnecessary duplication in dielectric research and to correlate the results. The results of this paper, when correlated with similar work being carried on elsewhere in this country, should add to our knowledge of the behavior of dielectrics under the action of direct current.

1. *Proc. Physical Soc. of London*, Vol. 27 (1915), p. 291.

F. W. Grover: I have been much interested in the paper by Professor Race because he deals with a subject on which I did some experimental work while at the Bureau of Standards. We studied what is called the absorbed charge of a condenser, that is, the charge that comes out of a condenser after it has been discharged and short-circuited for a while. In this study it seemed almost impossible ever to discharge a condenser. This is true of the best mica condensers which we used for standards at that time. In fact you might say that the condenser acted like a continuous, perennial source of energy.

But the thing that has interested me especially in the work of Professor Race is that a supposedly homogeneous substance like fused quartz should show this effect. That theory of dielectric absorption which has received the most attention and which has been regarded by most observers as offering an explanation for the *qualitative* phenomena, although perhaps not for the *quantitative*, is the law of stratified dielectric, brought out by Maxwell. According to that, it is a necessity with inhomogeneity of the dielectric that absorbed charges appear at the surfaces where the layers meet. But according to Professor Race a homogeneous substance also shows absorption. Some of the earlier investigators claimed that with substances believed to be perfectly homogeneous they found no absorption at all.

One observer, some ten years ago, working with thin layers of paraffine, claimed that if precautions were taken to insure the exclusion of air films, no absorption was found in this case also. The results obtained by Professor Race on fused quartz, on the contrary, although obtained with no chance for the presence of air films, show a well defined absorption effect.

I think this work is very instructive from the standpoint of dielectric theory.

A. S. Dana: I should like to ask Professor Race whether he thinks it is possible that the hard rubber showed the same phenomenon as the fused quartz (*i. e.*, the reversal during the first short period), but because the period was so short it escaped notice.

H. H. Race: In response to the last question, my object in this work was to obtain reliable quantitative data. Because the current changed very rapidly immediately after applying or removing potential, it was impossible to obtain quantitative data during the first minute. It was only in the case of fused quartz that unexpected reversals were observed and the apparatus changed so as to determine qualitatively at least the form of the current curve. In the case of hard rubber no such reversals were evident and no accurate data were sought during the first minute.

Interconnection of Power and Railroad Traction Systems by Means of Frequency Changers

BY LUDWIG ENCKE[1]

Associate, A. I. E. E.

Synopsis.—*Several types of variable ratio frequency-changers are discussed and installations of such apparatus on the electrified section of the New York, New Haven & Hartford Railroad are described in some detail.*

These types of frequency-changers permit a flexible tie between interconnected systems, and accurate and automatic control of load regardless of variations in voltage or frequency in either system.

Any desired constant load transfer in either direction may be obtained through the apparatus by manually setting a load regulating relay. Provision is made also for operating the sets as synchronous condensers to improve power factor.

The functioning of regulating machines and auxiliary equipment to obtain the desired results is explained, together with a description of switching equipment installed in connection with the main units.

A NUMBER of methods may be employed for connecting two power systems of different frequencies for interchange of power.

At the present time, a rigid tie by means of a synchronous motor-generator is common, and is in many respects the simplest form of connection. Since this rigid connection is wholly dependent upon both frequencies, it does not allow any regulation of the transferred load on the set itself. Furthermore the process of synchronizing is somewhat difficult, since for this purpose the frequency of one system or the other must be changed, and this of course can be done only at the power station. Another type of rigid tie which has been successfully employed consists (in the case for instance of a connection between systems of 60 and 25 cycle) of an induction machine, having a 60-cycle stator and a 25-cycle rotor, mounted on the same shaft with a 25-cycle synchronous machine. The slip-rings of the 25-cycle rotor of the induction machine are connected through a transformer, equipped with taps, to the 25-cycle system to which the synchronous machine is connected. This type of connection not only represents a power and frequency tie but also a voltage tie between the two systems.

A flexible connection is desirable in some instances, and obviously possesses fundamental advantages over any method of rigid tie, in that it permits not only merely tying together two power systems for interchange of power, but a close control of load as well. This may be of especial value in the supply of power for the operation of an electrified steam railroad extending over a large territory, from two or more central station generating plants located along the right-of-way at widely scattered points. In case of a single-phase electrified railroad, it may be necessary to change the 60-cycle power, available in most commercial power systems, into 25-cycle power necessary for traction purposes, at the same time operating in parallel with existing power plants owned by the railroad. By means of flexible connections any desired load distribution among different substations may thus be readily obtained, regardless of variations of frequency in any of the interconnected systems, all variations being absorbed in the machines themselves. Such flexible frequency-changer sets are known as "variable ratio" machines and usually consist of an induction machine, the speed of which is adjustable by means of auxiliary apparatus, mounted on a shaft with a synchronous machine. The speed regulating devices for the induction machine thus employed were originally designed for driving steel mills, etc., when variable speed was required. When used in connection with a frequency-changer set, the auxiliary apparatus usually consists of a three-phase commutator type machine with suitable exciting machines. Another method of obtaining the advantages of a flexible tie between power systems is the application of a rotary converter, (converting the alternating current of one frequency into direct current) in series with a second rotary converter "inverted," which in turn changes the direct current into alternating current of the other frequency. This method, however, is not in common use.

Recently a number of sets of the flexible frequency-changer type (motor-generator) has been purchased for use in connection with the New York, New Haven & Hartford Railroad's electrified system between New York and New Haven.

At present the single-phase 25-cycle system of the New York, New Haven & Hartford Railroad is fed mainly from the railroad's own power plant at Cos Cob, Connecticut. Power is supplied also from the Sherman Creek plant of the United Electric Light & Power Co. at New York. It has been found desirable with increasing loads to provide energy sources on the eastern end of the electric zone and connections have been made at New Haven with the 25-cycle system of the Connecticut Co., a subsidiary of the railroad operating the local street railway system, and at Devon, Connecticut, with the 60-cycle power system of the Connecticut Light & Power Co. In both instances, the connections are by means of "variable ratio frequency-changer sets," which are employed on account of the differences

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in frequency of the various systems involved, and for the ready control of the power. One unit has been installed in the power plant of the Connecticut Co. at New Haven and two units at Devon in a substation erected immediately outside the plant of the Connecticut Light & Power Co. All the sets are rated nominally at 5000 kw. A fourth set, a duplicate of the New Haven installation, has been installed in the Long Island Railroad's substation at East New York on the Bay Ridge line which has been recently electrified, together with the New York Connecting Railroad as an extension of the New Haven electrification system and receives its power from the New Haven supply. The East New York set is used normally as a rotary synchronous condenser, but is available for transferring power from the three-phase system of the Long Island and Pennsylvania Railroad to the single-phase system of the New Haven or vice versa, as a mutual standby.

Before describing the above mentioned installations in detail, a discussion of the general theory of the speed regulation of an induction motor may be of interest. The speed of an induction motor is fixed by the frequency of the power supply and the number of its poles. When a load is applied the rotor slips slightly, or loses speed. In order to obtain a regulation of the speed, resistance may be inserted in the rotor or secondary circuit of the motor. The current induced in the secondary circuit will thus decrease, and the result is a decrease of the torque and a consequent decrease of speed. Having reached a certain lesser number of revolutions, the current necessary for delivering the torque again flows in the motor's secondary on account of the increased slip voltage. Thus a certain amount of speed regulation of the motor may be obtained by inserting resistance in the rotor circuit. A disadvantage of this method is its lack of economy, since a part of the energy transmitted by the rotating field to the rotor is converted in the resistances into heat and is wasted. Furthermore, the speed regulation is not constant but changes with the torque or load on the motor and of course only regulation below synchronism is possible. Economical methods of regulation have been found in a number of arrangements. The slip energy of the induction motor may be transferred to an additional machine (the so-called regulating machine), where it may be transformed either into mechanical or electrical energy depending on the type of machine employed and thus utilized. By changing the excitation of the regulating machine a variable voltage is produced which, reacting upon the slip voltage, brings about the speed regulation of the induction motor.

The diagrams shown in Fig. 1 illustrate the speed regulation of an induction motor at speeds below synchronism.

Diagram A is the simplified diagram of an induction motor, disregarding reactance and the primary resistance of the machine.

E_1 is the primary voltage applied to the induction motor, producing in it the flux Φ; for this purpose the magnetizing current I_μ is taken from the line or supply. E_2 is the voltage induced in the secondary of the motor and I_2 is the secondary current. I_μ and I_2 determine the primary current I_1 taken from the line.

In diagram B is indicated a counter voltage E_{REG} introduced in the secondary of the induction motor. If the same torque is to be delivered by the motor, *i. e.*, if the same current I_2 flows through the rotor, the secondary or slip voltage must be increased to the new value of E_2'; thus the speed of the motor drops. $E_2' - E_{REG}$ results in the original secondary voltage E_2.

In diagram C it is seen that the regulating machine voltage E_{REG} is not displaced by 180 deg. against E_2, but by a certain angle Θ. This voltage E_{REG} may be split up into two components. E_R is the effective counter voltage; E_x is the compensating voltage. The current I_1 is almost in phase with the primary voltage; thus power at nearly unity power factor is taken from the supply. The wattless current necessary for the excitation of the induction motor is delivered by the regulating machine due to the compensating voltage E_x.

As indicated above, three-phase commutator ma-

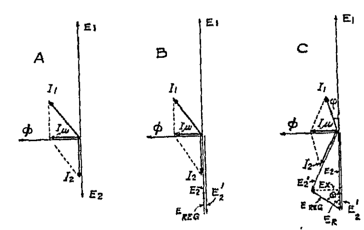


FIG. 1—DIAGRAMS ILLUSTRATING THE SPEED REGULATION OF AN INDUCTION MOTOR

chines are used as regulating machines for the frequency-changer sets discussed herein. They may be mechanically coupled or driven separately. If the regulating machine is mechanically coupled to the induction motor, *i. e.*, installed on the same shaft or geared to it, it operates as a motor, assisting in driving the main shaft. A portion of the energy from the stator to the rotor of the induction motor is transferred mechanically to the main shaft and a portion is transferred electrically to the regulating machine, being transformed by the regulating machine into mechanical power. Disregarding the losses, the balance diagram is shown in Fig. 2. At any speed, a uniform horsepower is transferred to the shaft; in other words, the arrangement is a constant horsepower drive and the torque increases inversely in proportion to the speed. If, on the other hand, the regulating machine is mechanically separated from the induction motor it may be used to drive a separate machine, such as an induction generator. Only a part of the energy transferred to the rotor of the main induction motor is thus utilized in driving the main shaft, the rest being returned to the line through the regulating machine and induction generator. Dis-

regarding the losses the balance is indicated in diagram Fig. 3. This arrangement therefore represents a constant torque drive, the horsepower of which increases in proportion to the speed.

Thus far regulation only below synchronism, or full-load speed has been discussed. By adding auxiliary

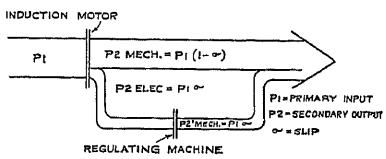


FIG. 2—BALANCE DIAGRAM FOR A CONSTANT HORSEPOWER DRIVE

apparatus the induction motor may be regulated up to and above synchronism. It is, of course, practically always desirable in the case of variable ratio frequency changers that speed be controlled above as well as below synchronism.

A normal induction motor can reach practically synchronous speed only under no-load conditions. Its full-load speed lies slightly below synchronous speed. When the voltage of the regulating machine is reversed, thus raising the slip voltage, the motor speed increases, and if this boosting voltage is high enough, the speed of the motor may be made to reach, and even pass above, synchronous speed. The induction motor thus operates as a doubly fed motor, the mechanical output of which is the sum of the energy supplied by the line to its stator and the energy supplied by the regulating machine to its rotor. During operation at exactly synchronous speed the slip voltage, and thus the electrical energy transmitted by the rotation field to the rotor winding of the main motor being zero, the total secondary energy is delivered from the regulating machine, the necessary excitation of that machine being furnished by the above

FIG.3.

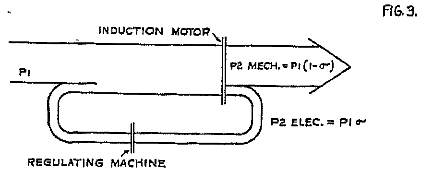


FIG. 3—BALANCE DIAGRAM FOR A CONSTANT TORQUE DRIVE

mentioned additional auxiliary apparatus. Above synchronism the direction of the slip voltage is reversed as compared to that of operation below synchronism. The resultant secondary voltage is again as in operation below synchronism the difference between the slip voltage and the voltage of the regulating machine. The secondary current, however, flows in the same direction. The relative directions of the voltage for speeds above and below synchronism are indicated in Table I, the directions for speeds below synchronism having been assumed arbitrarily. The tabulation shows clearly that the secondary current, as indicated, always takes the same direction, at speeds below synchronism as that of the slip voltage, and above synchronism as that of the voltage of the regulating machine.

The speed regulating set in which the regulating machine is mechanically connected to the main shaft also operates at speeds above synchronism as a constant

TABLE I
DIRECTION OF VOLTAGE AND CURRENT IN THE MAIN INDUCTION MOTOR AND THE REGULATING MACHINE FOR SPEEDS ABOVE AND BELOW SYNCHRONISM

	Below synchronism		Between full-load speed and synchronism		Above synchronism	
Machine	Voltage	Current	Voltage	Current	Voltage	Current
Ind. motor stator.......	↓	↓	↓	↓	↓	↓
Rotor.........	↑	↑	↑	↑	↓	↑
Reg. machine commutator.	↓	↑	↑	↑	↑	↑

horsepower drive. The additional power taken by the induction motor from the supply line is used to drive the regulating machine, which thus operates as a generator.

The arrangement in which the regulating machine is

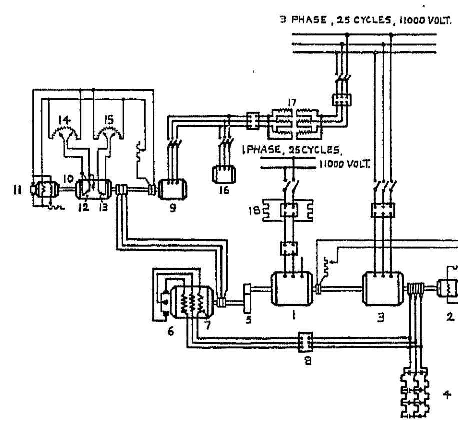


FIG. 4—DIAGRAM OF MAIN CONNECTIONS FOR THE FREQUENCY CHANGER SETS INSTALLED AT NEW HAVEN AND EAST NEW YORK

1. synchronous machine
2. d-c. exciter
3. main induction motor
4. secondary starting resistances
5. reduction gear
6. polyphase regulating machine
7. neutralizing windings
8. tie breaker
9. synchronous driving motor
10. a-c. exciter machine
11. d-c. exciter
12. load field windings
13. power-factor field winding
14. load field rheostat
15. power-factor rheostat
16. blower motor
17. auxiliary set transformer
18. current limiting resistances

mechanically separated from the main shaft is also a constant torque drive above synchronism. As the speed rises, the motor driving the regulating machine (*i. e.*, the induction generator now working as motor) takes increasing power from the line, which is supplied through the regulating machine to the secondary of the main induction motor.

Fig. 4 shows the wiring diagram of the frequency-changer sets installed in the New Haven and East New York substations. They consist of a main set and an auxiliary set. The main set is made up of a three-phase 25-cycle, 11,000-volt synchronous generator with d-c. exciter, a three-phase 25-cycle, 11,000-volt induction motor, the speed of which is determined by the synchronous generator, and the regulating machine which regulates the power flow of the set. The machines of the auxiliary set are, first a synchronous motor used for the drive, second a so-called a-c. exciter machine, and third a d-c. exciter, furnishing the excitation current for the other two machines. The induction motor, the synchronous generator, and the d-c. exciter of the main set are of standard design. The regulating machine is a rotor excited, neutralized a-c. commutator machine, the three-phase wound rotor having slip-rings and a commutator as in a rotary converter. Since the slip-rings carry alternating excitation current only, they are relatively small and the commutator segments are narrow, a feature of every a-c. commutator. The stator has a compensating winding which neutralizes the rotor field generated by the load current in the rotor, so that the machine can transform electrical energy to mechanical energy. The design of this machine is limited by the maximum permissible values of peripheral commutator speeds, the voltage between commutator bars and current densities, a satisfactory design thus requires that the kv-a. output per pole be somewhat limited, and it was desirable in order to obtain the required rating to build the machine at a slower speed than the main unit. The regulating machine, therefore, is connected to the main shaft through a reduction gear with a ratio of two to one and thus rotates at half the speed of the main set.

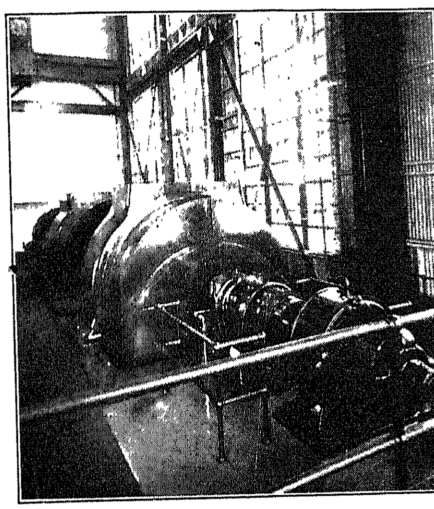


FIG. 5—VARIABLE RATIO FREQUENCY-CHANGER SET AT STATION "A," NEW HAVEN

In order to understand the operation of this machine, it may be assumed that the connections from its commutator brushes to the slip-rings of the main induction motor are cut off, and the slip-rings are connected directly to the line.

At stand-still a field will rotate with $n_1 = \dfrac{60\,\nu_1}{p}$ rev. per min. with regard to the stator and rotor, where

ν_1 = frequency of the line

$2\,p$ = number of poles of the machine.

In rotating the rotor with n revolutions opposite to the direction of the field, the resultant speed relative to the space will be:

$$n_1 - n$$

The voltage of the frequency $\nu_2 = \dfrac{p\,(n_1 - n)}{60} = s_2\,\nu_1$

is obtained at the brushes of the commutator, where

s_2 = slip.

The effective values of the voltages at the slip-rings and at the commutator brushes are practically equal. When $n_1 = n$, direct current appears at the brushes of the commutator. Therefore, if the regulating machine is given the same ratio of revolutions and number of poles as has the main induction motor, and the slip-rings are fed with line frequency, the slip frequency $\nu_2 = s_2\,\nu_1$ will always appear at the commutator brushes. Thus the commutator brushes of the regulating machine and the slip-rings of the main induction motor may be connected. As the voltages at the slip-rings and at the commutator brushes of the regulating machine are about the same, the latter, and thus the speed of the main set can be easily controlled by changing the voltage applied to the slip-rings of the regulating machine. It is a function of the auxiliary set to furnish to the slip-rings of the regulating machine this variable voltage at line frequency. The continuous delivery of line frequency is insured as the auxiliary set is a straight synchronous motor-generator, connected to the same line as the induction motor. The driving synchronous motor as well as the d-c. exciter are of standard design.

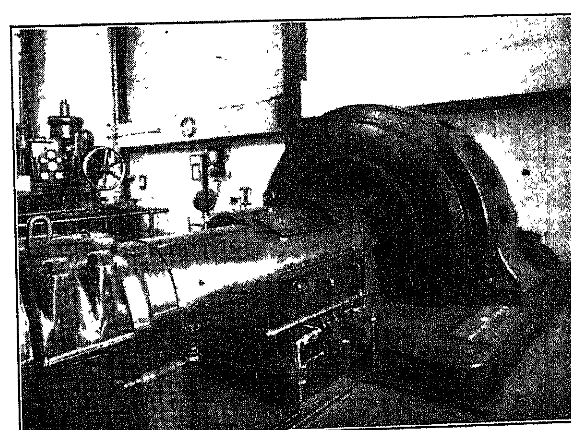


FIG. 6—REGULATING MACHINE AND REDUCTION GEAR OF THE MAIN MACHINE SET AT STATION "A," NEW HAVEN

The a-c. exciter machine resembles an induction motor. Its field consists of three windings with a phase

angle difference of 120 deg., two of which are connected in multiple. These windings independent of each other, excited by direct current, set up two fields which create a resultant field. The field of the two windings connected in multiple is the load field controlled by the load rheostat, whereas the field of the single winding is the power-factor field, 90 deg. out of phase with the load field, controlled by the power-factor rheostat. The load adjustment of the main set is obtained by changing the voltage generated in the a-c. exciter which is accomplished by varying the load rheostat, while the power factor of the main induction motor is adjusted by changing the power-factor rheostat which is of a potentiometer type. For running above synchronism the voltage of the regulating machine must be reversed; therefore the load rheostat is a reversing rheostat.

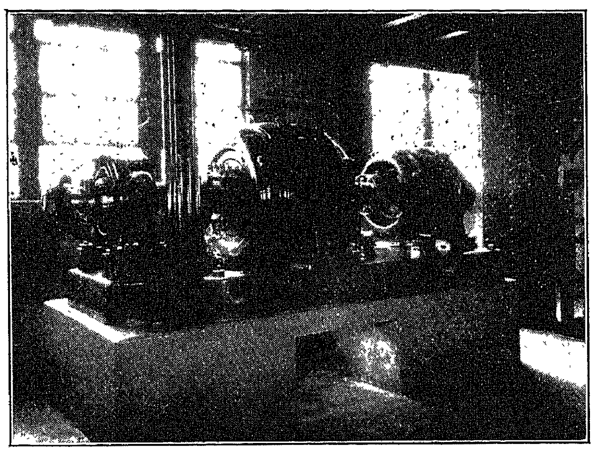


FIG. 7—AUXILIARY SET AT STATION "A," NEW HAVEN

Both the load and the power-factor rheostats are motor driven.

The following frequencies appear on the various machines and their connections:

1. From line to stator of induction motor... line frequency ν_1
2. In rotor of induction motor............. slip frequency ν_2
3. From slip-rings of induction motor to commutator of regulating machine.. slip frequency ν_2
4. From slip-rings of regulating machine to slip-rings of a-c. synchronous exciter.......................... line frequency ν_1
5. From stator synchronous motor to line............................ line frequency ν_1

The regulating set works as a constant horsepower drive, as all the energy taken from the line is transferred into mechanical power on the main shaft, neglecting the losses in the machines.

As outlined above this variable ratio frequency-changer set represents an interconnection between two 25-cycle systems. If, however, the induction motor is a 60-cycle machine the excitation for regulation would also be 60-cycle. The inherent frequency is then higher, a condition which is not desirable with rotor excitation on so large a set. Some other arrangement is thus necessary. This condition may be taken care of by replacing the rotor excited regulating machine by a stator excited type.

A slightly different means of regulation known as the Scherbius system is employed in the installation at Devon. The same system may be applied to connections between two 25-cycle systems or between a 60-cycle and a 25-cycle system.

Figs. 8, 9, 10 show single-line wiring diagrams for various applications, as follows:

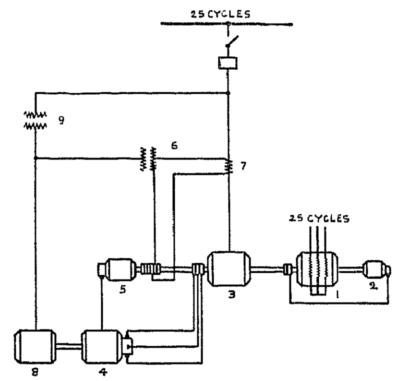


FIG. 8

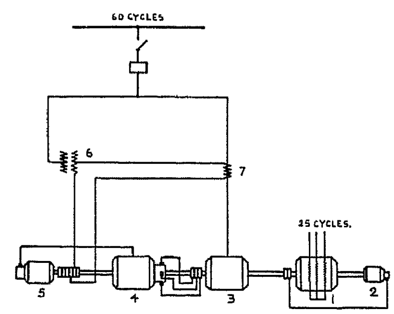


FIG. 9

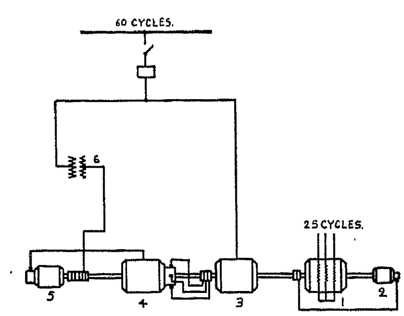


FIG. 10

FIGS. 8, 9, 10—SINGLE-LINE WIRING DIAGRAMS OF MAIN CONNECTIONS FOR SCHERBIUS CONTROLLED FREQUENCY CHANGER SETS

1. synchronous machine
2. d-c. exciter
3. main induction motor
4. regulating (Scherbius) machine
5. ohmic drop exciter
6. ohmic drop exciter transformer
7. bulging transformer
8. induction machine
9. power transformer

Fig. 8. Frequency changer suggested for a 25 cycle to 25 cycle tie.

Fig. 9. Frequency changer suggested for a 60 cycle to 25 cycle tie.

Fig. 10. Frequency changer 60 cycle to 25 cycle as in the substation at Devon.

These three wiring diagrams are perhaps especially interesting in their assemblage, in showing the progressive simplification.

Fig. 11 shows the three-line wiring diagram of the Devon set.

The frequency changer arrangement shown in Fig. 8 consists of a main and an auxiliary set. The latter includes the regulating machine and the induction machine, which at under synchronous speed operates as a generator driven by the regulating machine, and returns the slip energy back to the line. During

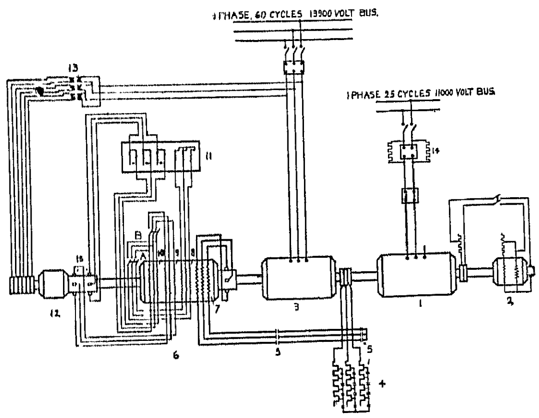


Fig. 11—Diagram of Main Connections for the Frequency-Changer Sets Installed at Devon

1. synchronous machine
2. d-c. exciter
3. main induction motor
4. secondary starting resistances
5. contactors
6. regulating (Scherbius) machine
7. neutralizing windings
8. power-factor control field windings
9. interpole field windings
10. load control field windings
11. power-factor rheostat
12. ohmic drop exciter
13. ohmic drop exciter transformer
14. current limiting resistances.

A & B contactors

15. movable brushes

operation above synchronism, however, the induction machine works as a motor and drives the regulating machine, which as a generator feeds the secondary of the main induction motor. The induction machine is of standard design. This set operates at a constant torque, while the arrangements shown in Figs. 9, 10, 11 show a constant horsepower drive, as the regulating machine is mounted on the main shaft.

The synchronous generator, its d-c. exciter, and the main induction motor have no unusual features. Common to these regulating sets and resembling in appearance a d-c. machine is the Scherbius regulating machine. Like a d-c. machine, it has main poles and interpoles. The excitation, however, is alternating current instead of direct current. As the frequency of the excitation voltage determines the frequency at the commutator brushes which are connected to the slip-rings of the main induction motor, the regulating machine must be excited with slip frequency. Furthermore, the voltage existing at the commutator brushes, and thus the speed of the regulating set, is controlled by varying the excitation voltage.

This excitation voltage is furnished from the line through a special auxiliary machine known as an ohmic drop exciter or frequency changing exciter which works as a frequency converter. Its operation resembles that of the regulating machine previously described. The rotor is analogous to the rotor of a rotary converter in that it is three-phase wound, and has slip-rings as well as a commutator. The stator has no field winding, and is merely a laminated steel ring to provide a flux path. The slip-rings are connected through a transformer to the line. Since it is mechanically coupled to the main induction motor and has the same number of poles, a voltage of slip frequency exists at its commutator brushes, which is employed for the excitation of the regulating machine. The commutator carries two sets of brushes which are moved by a brush-shifting device, and the regulation of the excitation voltage is accomplished by shifting these brushes. That is, by moving the brush-shifting device in one direction or the other, more or fewer commutator bars are included between the brushes, and the excitation voltage applied to the regulating machine is thus raised or lowered. The brush-shifting device provides for operation at under synchronous as well as above synchronous speed by reversing the excitation voltage. Two contactors A and B are provided in the connections between the ohmic drop exciter and the regulating machine. During under synchronous operation as well as at synchronous speed contactor B is closed, connecting the ohmic drop exciter to the Scherbius machine through its interpoles, whereas above synchronous speed the contactor A is closed, connecting the ohmic drop exciter directly to the Scherbius machine.

As in the regulating sets of other types, these sets also are equipped with apparatus to correct the power factor of the main induction motor. As shown in the wiring diagram Fig. 11, the so-called power-factor rheostat is connected in series with the load control field windings of the regulating machine. The degree of lag of the exciting current behind the voltage can be varied in changing the resistance of these windings by means of the rheostat. The regulating machine is equipped in addition with separate power-factor control windings, which are used when no excitation is supplied to the load control field circuit, the first method described for power factor correction being under these conditions ineffective. These separate power-factor control windings are connected from one set of brushes through a second section of the power-factor rheostat to a star point. The voltage supplied to the power-factor control windings is constant and about in quadrature to that of the load control field. As the

excitation in the load control windings is increased, the effect of the power-factor control windings is reduced. Before the application of the automatically controlled power-factor rheostat, which is described below, was contemplated, an additional apparatus for power factor correction known as a "bulging transformer" together with a manually operated power-factor rheostat was considered. As shown in the wiring diagrams Figs. 8 and 9, the ohmic drop exciter is fed by its line transformer through the secondary of the bulging transformer, while the stator current of the main induction motor (fed from the line) flows through the bulging transformer primary. The voltage induced in the secondary of the bulging transformer (varying with the load on the induction motor) and the voltage furnished by the ohmic drop exciter transformer, are out of phase, and when combined obviously create a resultant voltage. This resultant voltage applied to the slip-rings of the ohmic drop exciter, changes automatically with the load. Additional control is accomplished in this case, as indicated above, by means of a manually instead of an automatically operated power-factor rheostat. Both brush-shifting device and power-factor rheostat are motor operated.

All of the regulating sets discussed above are started from the induction motor side of the main set by inserting resistances in its secondary. When an auxiliary set is used, it is connected to the line at the same time or shortly before the main set. After the induction motor has reached its full speed, its secondary slip-rings are connected to the commutator of the regulating machine; thus, the load which is to be transferred and the power factor of the main motor may be adjusted. Full automatic starting of the sets has been provided in all cases.

TABLE II

TECHNICAL DATA SPECIFIED FOR THE VARIOUS FREQUENCY-CHANGER SETS

A	Frequency		Regulation per cent	No load speed		Generator kv-a.	D-c. exc. kw.	Ind. motor hp.	Reg. mach. kv-a.	Ind. mach. kv-a.	Ohm. Dr. exc. kv-a.	Syn. motor kv-a.	A-c. exc. kv-a.	D-c. exc. kw.	Reg. machines		Remarks
	mot.	gen.		Main set	Aux. set										No of r. mach.	Total kv-a. of reg. mach.	
A	25	25	6	750	750	7140	85	7200	450	..	..	45 (60 hp. 100% pf.)	150	16	4	661	Installed at New Haven
B	25	25	3	500	750	7140	85	7100	250	325	5	..	..	..	3	580	
C	60	25	8.4	500	..	7140	90	7200	500	..	45	..	..	..	2	545	Installed at Devon

B	System frequencies	Weights in pounds						Dimensions				
								Main-set		Auxiliary-set		
		Generator	D-c. exc.	Ind. motor	Bearings & accessories	Reg. mach.	Total	Length in.	Width in.	Length in.	Width in.	Total sq. yard
A	25 to 25							726	143	139	60	86.5
B	25 to 25	192,000	4000	90,750	39,000	24,900	350,650	443	180	131	67	68.3
C	60 to 25	192,000	4000	61,000	50,000	29,000	336,000	579	188	..	..	84.0

	System frequencies	Efficiencies			
		½ load %	¾ load %	1/1 load %	1½ load %
A	25 to 25	82.7	86.6	88.1	87.7
B	25 to 25			88.0	
C	60 to 25	80.3		86.9	88.0

The synchronous generators furnishing the single-phase railroad power are built as three-phase machines, having the single-phase rating as shown in Table IIA. The stators are all spring mounted, in order to reduce vibration due to the single-phase load. These springs are installed on both sides of the stators which are thus entirely supported by them. Leaf springs are used at New Haven and East New York, while at Devon, helical springs are employed.

All installations are equipped with automatic load regulators which, when adjusted for any given kw. value, provide that during all variations of frequency in the interconnected systems, within the allowed limits as described below, the transferred kw. load shall remain constant. Two different types of load regulators are used; in the New Haven and East New York substations a rheostatic type is installed, while those in the Devon substation are of a polyphase induction type.

The rheostatic type load regulator has as a control element two solenoids, one of which carries a current and a voltage coil, energized from a current and a potential transformer in the single-phase generator circuit, and connected in such a way, that its pull is proportional to the single-phase kw. load. The plunger of this solenoid acts on a lever arrangement, which carries a double acting circuit closing contact. The second solenoid which is energized through two d-c. coils acts on the same lever arrangement to prevent hunting. A variable anti-hunting rheostat is also connected into the circuit of one d-c. winding. Two dash pots stabilize the operation of the control element, and the pull of the alternating current aided by counterweights balances the weight of the core. A variable rheostat, a so-called load adjusting rheostat, is con-

nected in parallel to the current coil of the a-c. solenoid. By means of this rheostat, more or less current can be shunted through the a-c. coil, and various values of kw. load can be obtained by means of a calibration dial which is graduated in terms of kilowatts. The load regulator is in equilibrium for a given kw. value dependent on the position of the load adjusting rheostat. As soon as the output of the single-phase machine varies, this equilibrium is destroyed and the double acting contact mentioned above will close in one or the other direction. Two reversing contactor switches are provided and are energized over the main contact of the control element. If the load drops below the value for which the regulator is set, the main contact closes, energizing one of the reversing contactor switches, which in turn allows the current to flow through the armature of the motor driving the load rheostat and turning it in the "raise" direction. If the load increases above the value as fixed by the setting, the other reversing contactor switch is energized resulting in the rotation of the rheostat driving motor into the "lower" direction. The motor is a shunt motor, the field of which is permanently energized. The reversing contactor switches have two additional contacts, which are closed when the switches are deenergized. The motor and the switches are connected in such a way that the armature of the motor is short circuited when the additional contacts of both switches are closed. The dynamic braking, thus applied to the motor, stops it almost instantaneously when the control element's contacts are open, *i. e.*, when the regulator is in equilibrium.

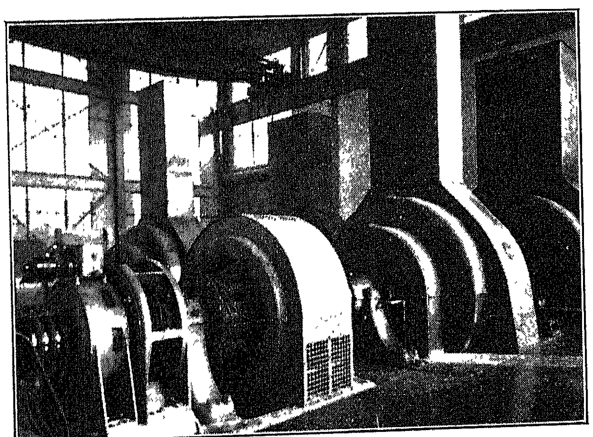


FIG. 12—VARIABLE RATIO FREQUENCY-CHANGER SETS IN THE SUBSTATION AT DEVON

The polyphase induction type load relay as installed at Devon is similar in its construction to a polyphase watthour meter. The relay has two stationary electromagnetic elements consisting of a current winding and a potential winding with laminated steel magnetic circuits. These windings are energized from a current and a potential transformer in the three-phase induction motor circuit and the two elements react on two disks on a single vertical shaft. They are suspended from a torsion wire and operate a double throw circuit closing contact. Two permanent magnets are used to damp the rotation of the disks. The torsion wire balances against the pull of the elements and its tension can be manually changed. For this purpose a knob and a scale graduated in kilowatts are provided, allowing the setting of the relay for each desired kw. value within the capacity of the machine set. As soon as the load varies from the value for which the relay has been set the

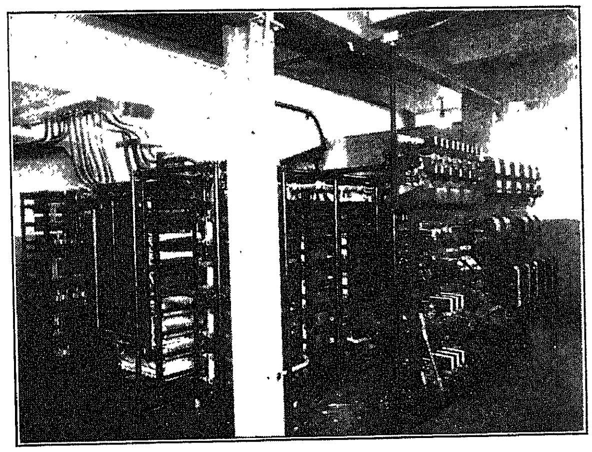


FIG. 13—SECONDARY STARTING PANEL AND RESISTANCES, AND POWER-FACTOR RHEOSTAT IN THE SUBSTATION AT DEVON

double throw main contact closes. This energizes by means of an instantaneous auxiliary relay the "raise" or "lower" relay, which in turn closes the armature circuit of the motor driving the brush-shifting device on the ohmic drop exciter in one direction or the other. These latter relays have also additional contacts, which are closed in order to permit dynamic braking, when the relays are deenergized. The armature of the motor, (which in this case is a series motor), is short-circuited when these contacts of both relays are closed, while the series field winding of the motor remains energized over an inserted resistance.

In all the substations, the load regulation of course can be performed manually as well as automatically. In the case of the New Haven and East New York substations a two-position control switch is provided to accomplish these two modes of operations, while at Devon, a control switch for the manual operation and a transfer switch for changing to automatic control are installed. The technique of placing the machines under the control of the automatic regulators is very simple in all the installations. After the generator is synchronized with the railroad power system, the control switch or the transfer switch is placed in its "regulating" position and the load adjusting rheostat at New Haven and East New York and the knob of the load relay at the Devon substation are adjusted slowly until the pointers indicate on the scale the load which it is desired to carry.

All frequency-changer sets under discussion can of course fundamentally transfer power in either direction; nevertheless only the sets at New Haven and East New York are specifically intended for interchange of power, the installation at Devon being arranged to transfer power only from the 60-cycle system to the 25-cycle system.

The range of the frequency regulation of the sets is shown in Table IIA.

The regulating sets installed at the New Haven and East New York substations (Fig. 4) and at Devon (Fig. 11) as mentioned above are constant horsepower drives. In the design of speed control for steel mill motors the decision as between a constant horsepower or a constant torque drive is determined by local operating conditions. This does not apply to frequency changers, and either form of drive may be applied. Nevertheless the demands of a frequency changer are of course more those of merely a constant horsepower drive. When the machines are once adjusted for a given load the transferred horsepower must remain constant independent of frequency (*i. e.*, speed variation) in either or both of the two systems connected. It is to be noted that a constant horsepower drive, as has been pointed out, involves one auxiliary machine less than a constant torque drive.

Table II contains technical data of interest in connection with the various sets discussed.

Having considered the different types of variable ratio frequency changer sets, it may be of interest to note briefly the general layout, the switching equipment, the protective devices, and the operating conditions of the machine sets installed in the two substations at New Haven and at Devon.

The variable-ratio frequency-changer set at New Haven has been installed as an interconnection between the systems of the N. Y., N. H. & H. R. R. Co. and of the Connecticut Co., in the power plant of the latter company at New Haven, Connecticut, which is known as Station A. The existing power plant building has been extended one bay and the main set is installed on the operating floor, with the auxiliary set on the main floor below. A mezzanine platform was erected on the steel foundation of the main unit, between the main and the auxiliary sets, for the secondary resistances of the main induction motor, the load and power-factor rheostats and the tie breaker. The switching equipment and the switchboard are built as extensions to the existing equipment of the Connecticut Co. and conform as far as possible to existing conditions. All operations for starting and operation of the set are controlled from the switchboard. The main induction motor is designed for forced ventilation by means of a motor-driven fan. The bearings of the main set are water-cooled and self lubricating.

Fig. 14 shows a wiring diagram of the machine set and indicates the instruments and protective devices used. The automatic protection of the set includes the protection of the various machine units and the means to secure the proper starting sequence. The main induction motor as well as the generator is equipped with differential relays to protect against internal faults. For the protection of the synchronous generator against excessive overload, especially when operating as a condenser, the voltage regulator is provided with a device for limiting the field current. The auxiliary set together with the blower motor is fed through fuses from the 440-volt auxiliary busses of the power plant.

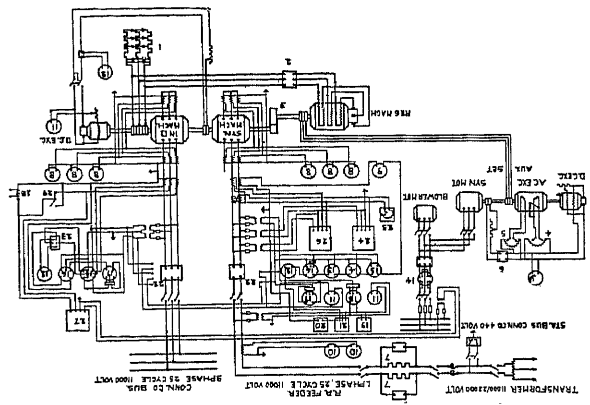


Fig. 14—Wiring Diagram of Frequency-Changer Substation at New Haven

1. secondary starting resistances
2. tie breaker (oil circuit breaker)
3. reduction gear
4. load field rheostat
5. power-factor rheostat
6. field transfer switch
7. current limiting resistance
8. differential protection relay
9. emergency overload relay with a high time setting
10. overload relay used for controling the operation of the oil circuit breakers shunting the current limiting resistances
11. voltmeter
12. ammeter
13. wattmeter
14. watthour meter
15. reactive volt ammeter
16. power-factor meter
17. frequency meter
18. synchronoscope
19. graphic voltmeter
20. graphic ammeter
21. graphic wattmeter
22. voltmeter switch
23. ammeter switch
24. load regulator
25. load adjusting rheostat
26. voltage regulator
27. power-factor regulator
28. auto transformer feeding the accelerating relays
29. auxiliary switch of tie breaker, shown in open position of tie breaker

A number of interlocking devices provides a proper starting sequence. The starting of the set is possible only when the load field rheostat and the power-factor rheostat are in their neutral positions, to which they are brought manually. Furthermore the tie breaker connecting the slip-rings of the main induction motor to the commutator brushes of the regulating machine must be opened. For this purpose, this breaker is interlocked with that of the main induction motor in such a way that tripping the latter trips the tie breaker

automatically. An interlock between the breaker of the auxiliary set and the main induction motor breaker insures that when one trips the other one is tripped automatically. The load and the power-factor rheostats being in proper positions, the closing of the control switch of the main induction motor breaker opens the starting sequence. The secondary resistances of the main motor are short-circuited step by step, as controlled by accelerating relays, which allow the short-circuiting of the next resistance step only after the primary current is lowered sufficiently. At the same time, the auxiliary set and the blower motor start. Full voltage is applied to the stator of the synchronous driving motor of the auxiliary set (which is provided with a damper winding), and its field is short-circuited over the field discharge resistance. After reaching full speed and after building up the voltage of the d-c. exciter of the auxiliary set, the discharge circuit is opened and the field is connected to the d-c. exciter machine, and the tie breaker closes. The speed regulation can now be applied by manipulating the load-field rheostat, facilitating the synchronizing of the generator with the railroad supply. The blower motor is a squirrel-cage motor, which is started with full voltage and speeds up to its constant speed. The set is now ready to supply power from one system to the other.

Typical for every single-phase railroad load are the heavy and sudden swings of the load in kilowatts as well as the reactive kv-a. load. Nevertheless, in putting the machine under the control of the automatic load regulator, a given kw. load representing a base can be accurately maintained, while the swings are taken up by another source of supply. Any desired load within the capacity of the machine can thus be adjusted. Fig. 15 shows such a kw. curve; in this instance the automatic load regulator was adjusted for a value of 5000 kw., and it is of interest to note how the load was kept constant within comparatively narrow limits, in spite of the widely varying system load.

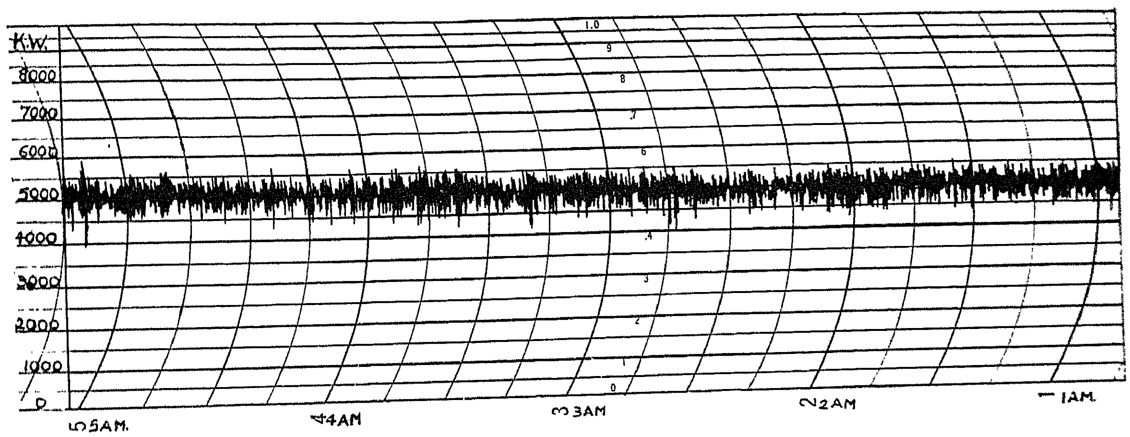


Fig. 15—Kw. Load on the Frequency-Changer Set at New Haven

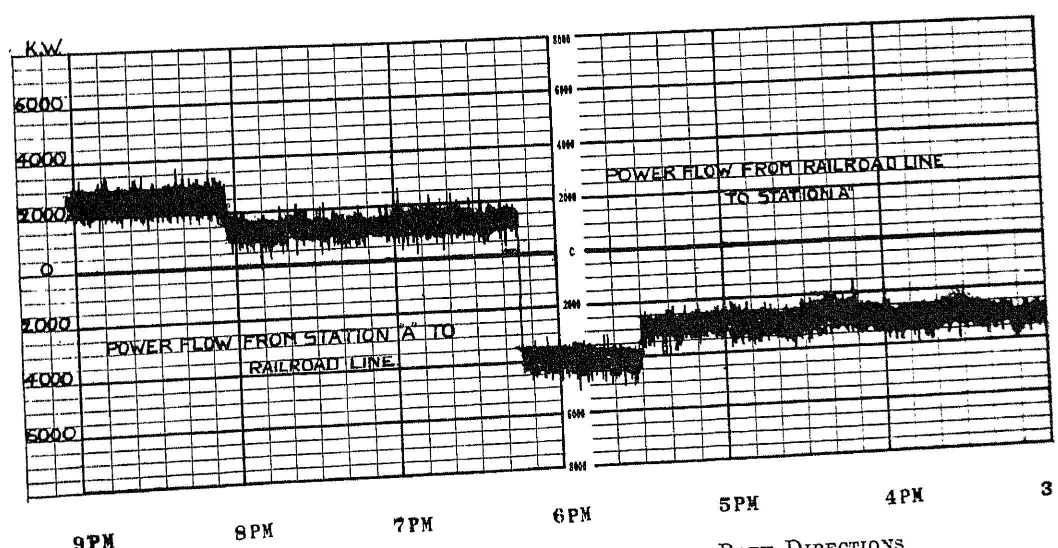


Fig. 16—Kw. Load Curve for Power Flow in Both Directions

As previously mentioned the sets at New Haven and East New York have been arranged for power flow in both directions. Fig. 16 shows such an operation.

The sets at New Haven and at Devon as well as that at East New York are operated part of the time as motor-

generators and part as synchronous condensers. It is obvious that when running as a synchronous condenser, a constant wattless output cannot be sustained if the voltage is to remain constant. The wattless output of lagging current or in other words the wattless input of leading current is carried by the machine as may be necessary; that is, the machine performs the function of keeping up the line voltage by putting out wattless current to take care of the wattless load. During such a period, the power plant at Cos Cob, of course, shows a power-factor improvement. But as soon as the "moving" wattless load is in the vicinity of Cos Cob, the wattless current is furnished from there, and the synchronous condenser at New Haven thus runs more or less idle. Obviously, it would be impossible to keep constant the reactive kv-a. load of the synchronous condenser, since the voltage regulator is set for maintaining voltage at a desired value and tends to keep this voltage constant by varying the excitation of the machine; that is, for carrying varying reactive kv-a. load. It is for this reason, as above stated, that the regulator is equipped with a current-limiting device, which, as soon as the machine is overloaded, reduces the voltage and in doing so the wattless current carried. Safe operation as a rotary condenser without this current-limiting device would be difficult. Figs. 17A and B show the operation of the machine at New Haven as a synchronous condenser under normal conditions. A represents the amperes carried and B the voltage. Figs. 18A and B represent also synchronous condenser operation but under unusually severe load conditions. The ampere curve is of interest on account of showing the highly swinging wattless load; the influence of the current-limiting device can be recognized very clearly in the voltage curve.

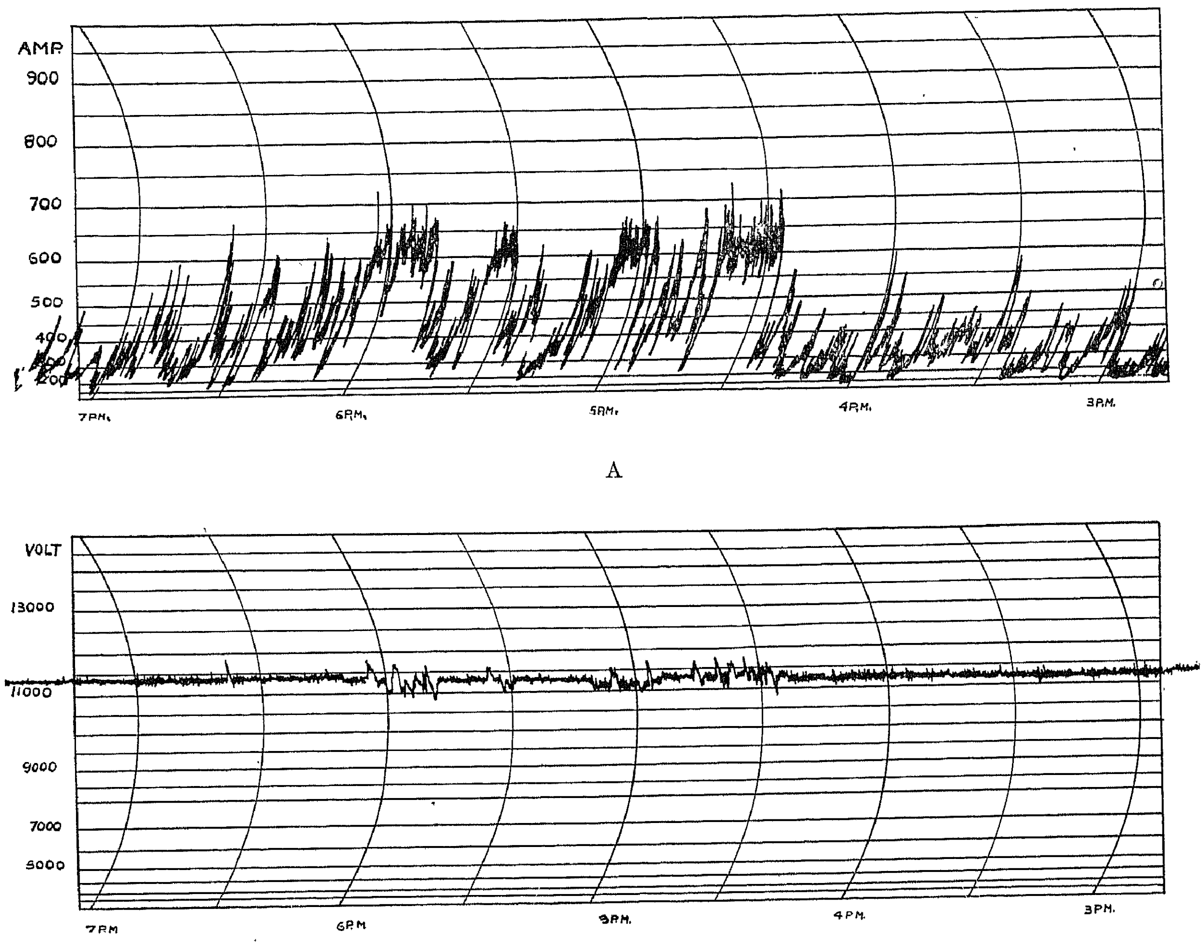


Fig. 17—New Haven Machine, Running as Synchronous Condenser

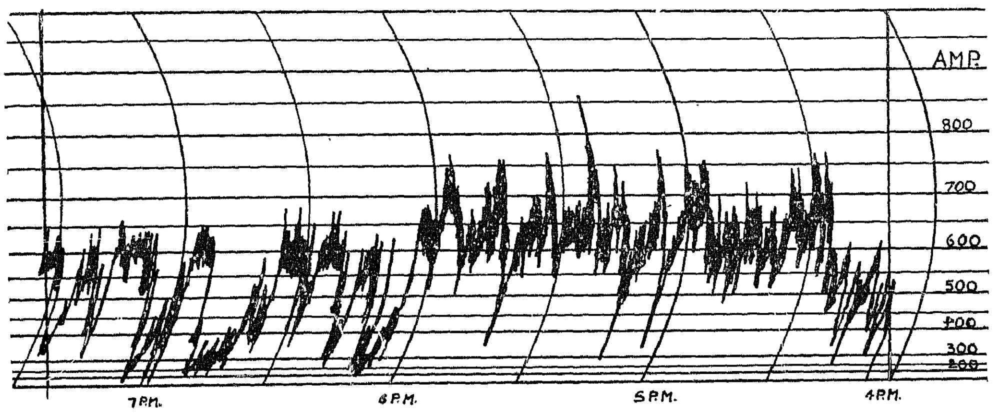
a = current b = voltage at terminals

At Devon, Connecticut, where is located the interconnection between the systems of the N. Y. N. H. & H. R. R. Co. and of the Connecticut Light & Power Co., a substation building was erected outside the power plant for housing the frequency-changer sets and their associated equipment. The two machine sets are installed on the main floor, and the auxiliary equipment, such as secondary starting panels and resistances for the main induction motors, the various

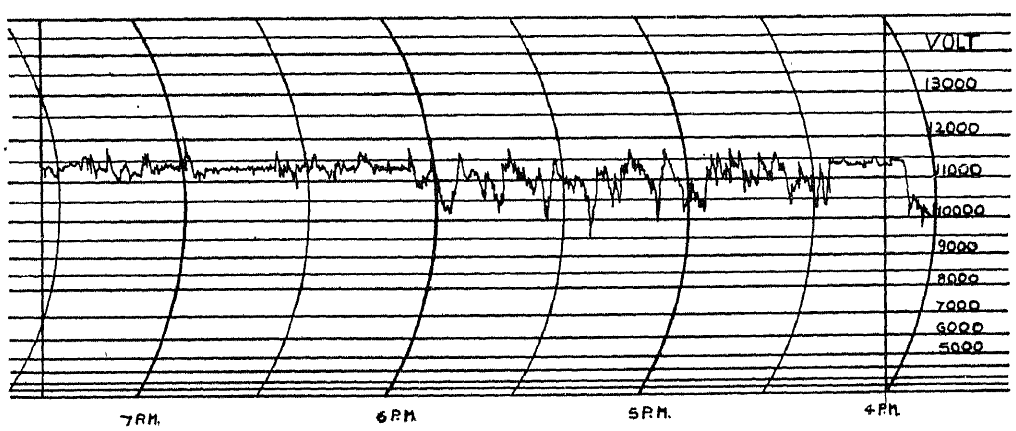
rheostats, and the transformers for the ohmic drop exciters, in the basement. A special room is provided for the switchboard. Outside of the building on one side are the 60-cycle busses, transformers, oil circuit breakers, and the incoming feeders, while on the opposite side are located the 25-cycle busses, transformers, and outgoing feeders to the railroad system. The substation is operated by the Connecticut Light & Power Company.

All machines are self ventilated. The single-phase generators, as above stated, may be operated as which operates to open the main breakers, thus shutting down the whole set. The synchronous generators are protected against excessive overload by a current limiting relay connected to the voltage regulators. Before starting, the power-factor rheostat is in its "all in" position and the brushes of the ohmic drop exciter in their neutral position, having been brought to these positions automatically when the set was shut down.

These sets are started automatically by simply closing



A



B

Fig. 18—Synchronous Machine at New Haven, When Running as a Synchronous Condenser Under Unusually Heavy System Load Conditions

a = current b = voltage at terminals

synchronous condensers. The bearings are water-cooled and self lubricating during running; during starting, however, an oil pump supplies oil under pressure to lift the rotating element from the bearings in order to reduce the break-away torque.

Fig. 19 shows the wiring diagram indicating the instruments and protective devices used. Here, too, the main machines are protected by differential relays against internal faults. In addition the induction motor circuits are equipped with overload relays. The ohmic drop exciters also have overload protection, the main induction motor circuit breaker. The secondary resistances of the induction motor are short circuited step by step, as controlled by timing relays, which allow the short-circuiting of the next resistance step only after a certain given time, the steps in this instance not being a function of current. The final connection between the slip-rings of the main induction motor and the commutator brushes of the regulating machine is performed by contactors as the last step of the starting sequence.

Normally one set only is operated either as a tie or as

a synchronous condenser, the other one being held as a spare unit except in emergency. Fig. 20 shows a kw. curve, when the machine is under the control of the automatic load regulator. This curve is of interest in comparison with Fig. 21, which shows the typical

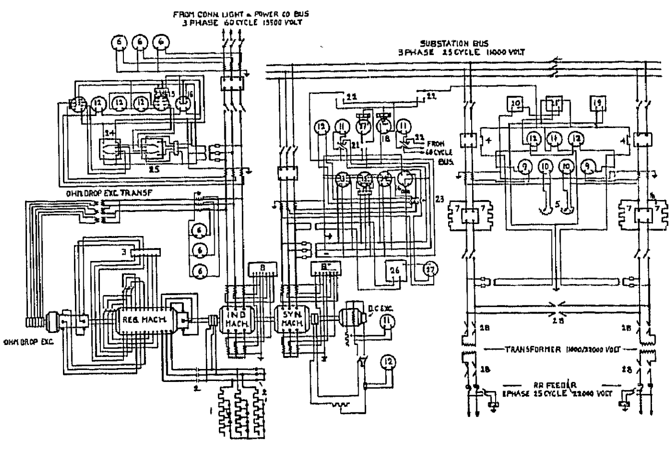


Fig. 19—Wiring Diagram of Frequency-Changer Sets and the Outgoing Railroad Feeders of the Substation at Devon (One Set Only Indicated)

1. secondary starting resistances
2 contactors
3. power-factor rheostat
4. auxiliary switch of feeder breaker. Only one feeder can be used for supplying power to the railroad system at the same time
5. adjusting rheostat for overload relay No. 10
6. overload relay
7. current limiting resistance
8. differential protection relay
9. emergency overload relay with a high-time setting
10. overload relay used for controling the operation of the oil circuit breakers shunting the current-limiting resistances
11. voltmeter
12. ammeter
13. wattmeter
14. watthour meter
15. reactive volt ammeter
16. power-factor meter
17. frequency meter
18. synchronoscope
19. graphic voltmeter
20. graphic ammeter
21. graphic wattmeter
22. V. M., Fr M., synchronoscope plug
23. A. M. jack
24. load regulator
25. power-factor regulator
26. voltage regulator
27. current limiting relay for voltage regulator
28. horn gap switch

variation of the kw. output of the power station at Cos Cob to the eastern part of the line. Figs. 22A and B show the ampere and the voltage curves, when operating as a synchronous condenser. As stated previously, the automatic load regulator in the case of the New Haven set is controlled by the single-phase output of the synchronous generator, whereas the automatic load regulator of the Devon set is inserted in the three-phase circuit of the main induction motor.

All frequency-changer sets are equipped with automatic reactive kv-a. regulators for the main induction motor. They are similar in construction and operation to the load regulators already described. The regulator installed in the New Haven substation maintains a power factor of approximately 100 per cent under all load and frequency conditions, and does not allow any adjustment. The automatic kv-a. regulator at Devon, however, maintains a constant reactive kv-a. value of the induction motor, which can be adjusted to any value in such a way that for every load setting a power factor up to 90 per cent or even to 100 per cent may be reached. These automatic kv-a. regulators are desirable to increase the simplicity of operation, inasmuch as in the course of maintaining a constant predetermined load on the sets, regardless of frequency variations in the interconnected systems, the power factor of the main motors may be affected.

One feature of interest common to the installations at New Haven and Devon is the protective arrangement to obtain selective operation on short circuits on the single-phase railroad system. Current-limiting resistances are installed on the single-phase ends of the machines, which are normally short-circuited by circuit breakers. In the event of a fault or ground on the railroad system, these resistances are automatically inserted by opening the circuit breakers, after which the local sectionalizing circuit breakers on the line feeding the fault are allowed to trip. The resistances are automatically short-circuited after the faulty section is cut out, and normal operation is resumed. In case of the failure of the line breakers to clear the line, the whole substation is separated from the railroad line after a predetermined time by the opening of the main circuit breakers.

The installations at Devon and New Haven were

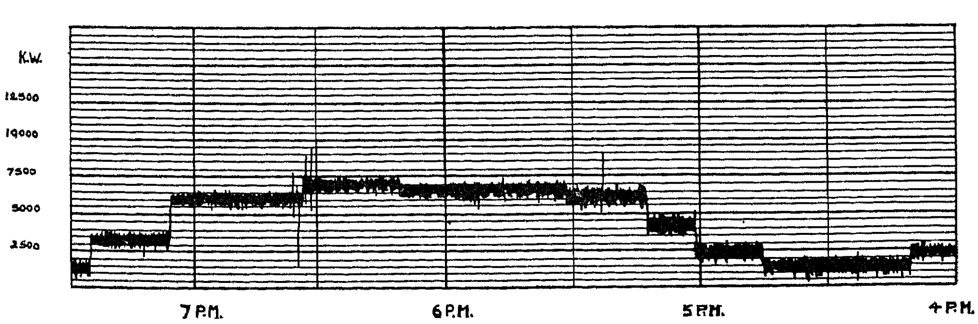


Fig. 20—Kw. Load on the Frequency-Changer Set at Devon

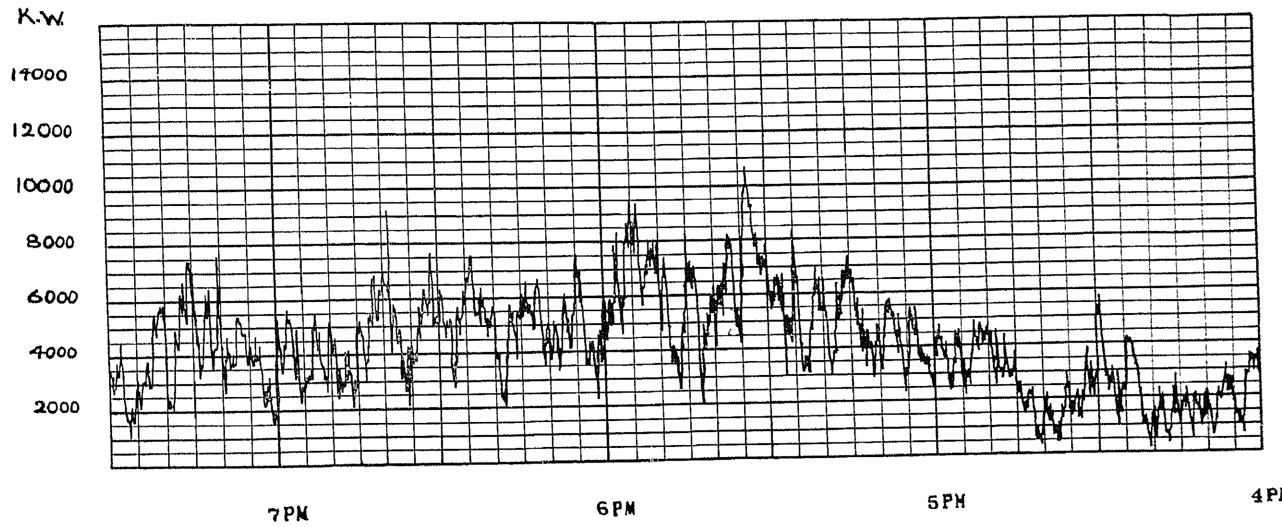


Fig. 21—Kw. Load Curve of the Power Station at Cos Cob, Contemporaneous with Conditions Shown in Fig. 15

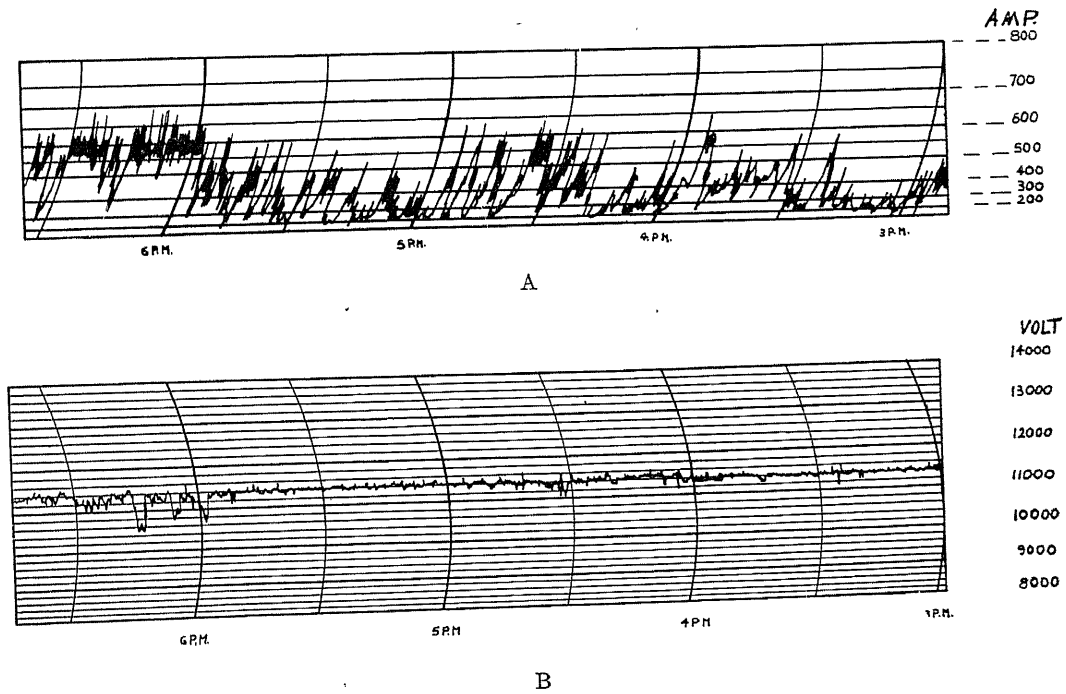


Fig. 22—Synchronous Machine at Devon, Running as Synchronous Condenser

a = current b = voltage at terminals

made under the general direction of Sidney Withington, Electrical Engineer of the New York, New Haven & Hartford Railroad, H. F. Brown, Asst. Electrical Engineer, and the writer. That at East New York was under the general direction of L. S. Wells, Electrical Superintendent of the Long Island Railroad. Messrs. Gibbs & Hill, New York, acted as consulting engineers for all the installations.

Discussion

For discussion of this paper see page 1079.

Application of Large Frequency Converters to Power Systems

BY E. J. BURNHAM[1]

APPLICATION OF LARGE FREQUENCY CONVERTERS TO POWER SYSTEMS

In selecting a frequency converter, there are many things which should receive special study and consideration in order that the equipment obtained will meet the necessary requirements in the best possible way.

The purpose of this paper is to discuss frequency converter sets and their use as a means of connecting systems of different frequency.

Systems of different frequency are connected together for the same reasons that systems of the same frequency are connected; namely, to save capital investment in generating equipment, and improve service to customers. By interconnection, the generating capacity of one system is made available for another, which may mean a large total saving and furthermore provides another source of power supply which may be of great value in emergencies when stations or transmission lines are out of service.

A somewhat different application is the use of frequency converter sets to connect power systems with railway and industrial systems, where the frequency of the power required by the railway or industrial load is different from the power system frequency.

The different points to be considered in choosing a frequency converter are considerably interwoven, so at best a compromise selection may be necessary. The type of set to be used should, without doubt, be determined largely by the particular characteristics and the operating requirements of the two systems to be interconnected. However, there are other points which may require special consideration, such as design, efficiency, operation, maintenance, and cost.

TYPES OF FREQUENCY CONVERTERS

The following types of frequency converters will be considered:

1. Synchronous-synchronous type, consisting of a synchronous motor direct-connected to a synchronous generator.

2. Induction-synchronous type, consisting of an ordinary induction motor direct-connected to a synchronous generator.

3. Adjustable-ratio induction-synchronous type, consisting of a wound rotor induction motor direct-connected to a synchronous generator, the induction motor having suitable control equipment to give a variable frequency ratio between the two systems to be connected together.

4. Fixed-ratio induction-synchronous type, consisting of an induction frequency converter direct-connected to a synchronous generator. The rotor of the induction motor is connected electrically to the stator of the synchronous unit, thereby allowing electrical, as well as mechanical transfer of power through the set.

SYNCHRONOUS-SYNCHRONOUS TYPE

With the synchronous-synchronous type of frequency converter, both units necessarily operate in synchronism, forming a rigid frequency tie between the two systems connected together. Therefore, with this type of set, the ratio between the frequencies of the two systems must normally remain constant.

In the past, the majority of frequency converter sets used have been of the synchronous-synchronous type because such sets are adaptable to simplicity of design and operation and may have low costs, high efficiency, and ability to correct power factor. Sets of this type can be sturdy and simple in design and have a minimum number of auxiliary parts. This results in minimum attention and low maintenance costs, which are important points.

The power factor of either machine may be conveniently adjusted by field control. Furthermore, if the set is not being used as a tie, either machine may be used as a synchronous condenser.

The load transferred through this type of set must be controlled by governor adjustments on the prime movers of either or both interconnected systems. Usually, this introduces no great hardship in operation, but in some cases it is a very inconvenient way of holding load on the frequency converters, particularly if the principal generating units of the interconnected systems are controlled by other companies.

In case it is desirable to synchronize the two systems at a frequency converter station, the governors of the prime movers must be adjusted until synchronizing can be accomplished. This again may be inconvenient, as it usually means telephoning to some distant generating station.

In using a frequency converter set of the synchronous-synchronous type, the capacity of the set may be determined by the size of the set that will reasonably hold the two systems together, rather than by the size of set required to transfer the amount of power desired. This would be a hardship in case it should be desired to transfer a small amount of power between two large systems of different frequencies.

Although normally the ratio of the frequencies at each end of a synchronous-synchronous set must remain constant, nevertheless there may be fluctuations in frequency or frequency ratio. Fluctuation in

1. Central Station Engg. Dept., General Electric Co., Schenectady, N. Y.

Presented at the Northeastern District, No. 1, Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

frequency on either or both systems causes load variation on the set and if the fluctuations in frequencies are severe enough, the set will pull out of step. Synchronous machines of this class are normally designed for 50 per cent momentary overload before the pull-out point is reached. In special cases, frequency converter sets may be designed for greater momentary overloads reaching values as high as 200 per cent. This means that momentary fluctuations in frequency or frequency ratio may occur and a set still maintain synchronous operation, provided load changes do not load the set above the pull-out point.

Excitation for the fields of the synchronous machines may be provided by two direct-connected exciters, one mounted on each end of the set, each arranged to excite the field of one synchronous unit. This gives a very flexible and dependable method of excitation. Sometimes the excitation for both main units is obtained from one direct-connected, or one motor-driven exciter.

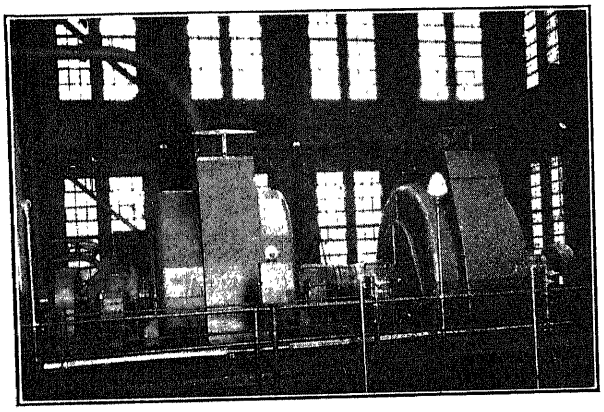


Fig. 1—20,000-Kw., 300 Rev. per Min. Synchronous-Synchronous Frequency Converter

With this arrangement, individual field control is obtained by the use of rheostats in the field circuit of the main units. The use of such rheostats introduces rheostat losses, and furthermore, the use of a common excitation scheme has the disadvantage that any excitation trouble involves the excitation of both units.

Motor-operated, phase-shifting devices may be furnished on frequency converter sets when the sets are to operate in parallel. Such a device mounted on one of the machines of each set permits control of load division between sets and enables the operator to add, or remove, a set from the line without any sudden jolt to the system. The phase shifting is accomplished by mounting the stator of one of the machines of the set in a cradle in such a manner that the stator may be physically rotated with respect to the stator of the other unit.

Fig. 1 shows a 20,000-kw. 300-rev. per min. synchronous-synchronous frequency converter recently placed in operation at Providence, Rhode Island, to connect the New England Power Co. 60-cycle system with the United Electric Railway 25-cycle system. The 60-cycle machine is rated three-phase 11,000 volts unity power factor and the 25-cycle machine is rated single-phase 11,000 volts unity power factor. The tested over-all efficiency of the set is 96.26 per cent.

Induction-Synchronous Type

Sets of the induction-synchronous type consist of an induction motor driving a synchronous generator and are very similar in normal operation to the synchronous-synchronous type of set, except that the frequency ratio varies slightly with load on the set, due to the slip of the induction motor. The induction motor may be either of the squirrel-cage or the wound-rotor type. The load on one of these sets is controlled in the same manner as the load on a synchronous-synchronous type of set, namely, by adjustment on the governors of the prime movers of either or both systems interconnected. When load on the set is changed, the ratio of frequencies on the two systems is necessarily changed at the same time, which is an undesirable factor in some cases. The straight induction motor, of course, lacks in itself the ability to correct power factor, and therefore cannot furnish leading current, or be utilized as a synchronous condenser when the set is not in use as a tie.

Division of load between two sets operating in multiple cannot be accomplished by a stator phase shifting device, because two induction synchronous sets operating in multiple will divide load according to their speed regulation, and not in accordance with difference in phase position. A change in phase position will not change the speed; therefore the load will remain the same.

Adjustable-Ratio Induction-Synchronous Type

By means of frequency-converter sets of this type, flexible frequency ties are formed between the systems connected together. The two main units consist of a synchronous machine direct-connected to a wound-rotor type induction machine. These two units are not required to operate in synchronism, as was the case with the synchronous-synchronous type. By means of auxiliary equipment, the direction and amount of power transferred through the set is controlled while the frequencies, or frequency ratio, of the two systems may vary within the limits for which the apparatus is designed.

The outstanding features of this type of set are as follows:

1. The ratio of the two system frequencies may vary.
2. Direction and amount of load transferred through the set may be controlled at the set itself.
3. The speed of the set may be controlled for synchronizing purposes.
4. The capacity of the set is determined only by the amount of power to be transferred through the set, as it is not necessary to furnish synchronizing power to hold the two systems together.

5. Leading current for power-factor correction may be furnished by the set to either system.

6. System disturbances will not pull the set out of step as easily as a set of the synchronous-synchronous type.

The synchronous unit of the set is of standard construction, such as used in the ordinary synchronous-synchronous frequency-converter set. The induction unit is of standard three-phase construction with phase-wound rotor, the selection of the secondary voltage being suitable for operation with auxiliary equipment to be described later.

Power may be transferred through the set in either direction by speed control of the induction unit which tends to make the machine operate above or below synchronism. Due to the fact that the speed of the set actually follows the speed of the synchronous unit, any tendency to increase the speed of the induction unit causes flow of power from the induction to the synchronous end and any tendency to decrease the speed of the induction unit causes flow of power from the synchronous to the induction end. The control of power flow in this manner is very similar to the control of a prime mover direct connected to a generator, where output is governed by speed control.

Several methods[2] have been developed for operating induction machines above and below synchronism, one of the principal applications being in steel mill work. The schemes so developed are available for controlling induction machines of adjustable-ratio frequency converters.

All of the schemes referred to are based upon the fundamental principle that the speed of an induction motor may be controlled by controlling its secondary voltage. In the ordinary induction motor, the speed is controlled by adjusting the secondary resistance, increased resistance having the effect of increasing the voltage drop in the resistors and opposing the flow of secondary current. The slip of the induction machine must always be such as to generate voltage sufficient to force through the impedance of the secondary circuit, the amount of current necessary to develop the required torque. If external resistors are used in the rotor circuit to control the speed, the secondary voltage across the resistors is always at slip frequency.

The resistance method of controlling speed of induction motors is not entirely suitable for use in controlling the induction machine of an adjustable-ratio frequency converter, because by this method, only speed control below synchronism is obtained for motor operation and only above synchronism for generator operation. Furthermore, this method permits undesirable rheostat losses. In order to have speed control of the induction machine above, below, and at synchronous speeds for a definite direction of power flow, some scheme such as used for control of steel mill motors is necessary.

In these schemes, the resistor is replaced by a regulating machine, which inserts a voltage of slip frequency in the rotor circuit of the induction unit. When this regulating machine operates as a motor, power is taken from the induction motor rotor, just as would be the case if a resistor were used, but with less loss. When the regulating machine operates as a generator, it corresponds to a negative resistance placed in the induction motor rotor circuit, furnishing power to the induction motor rotor, and giving speed control above synchronism.

In order to present a better idea of just how one of these regulating machines may be applied to an adjustable ratio frequency converter, some of the details of the Scherbius type sets will be mentioned.

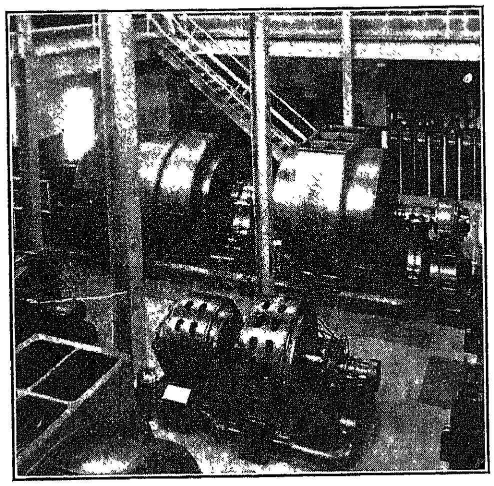


FIG. 2—6000-KW. ADJUSTABLE-RATIO INDUCTION-SYNCHRONOUS FREQUENCY CONVERTER

Regulating set is shown in foreground—Installation is in Rochester substation

Seven adjustable ratio frequency converters of the Scherbius-controlled type are now in operation. Five of these sets are rated 6000 kw., and two are rated 5000 kw.

Two of the 6000-kw. sets were installed in 1924, at Rochester, N. Y., where they connect the Niagara, Lockport & Ontario Power 25-cycle system with the Rochester Gas & Electric Company 60-cycle system, (see Fig. 2). Two additional 6000-kw. sets were installed in 1925 at Altmar, N. Y., where they connect the 25-cycle system of the Niagara, Lockport & Ontario Power Company with the 60-cycle systems of the Northern New York Utilities and Mohawk-Hudson. The other 6000-kw. set was installed at Falconer, N. Y., to form a connection between the Niagara, Lockport, & Ontario Power Company 25-cycle system and the 60-cycle systems of Western Pennsylvania. The two 5000-kw. Scherbius-controlled sets were recently in-

2. *Theory of Speed and Power Factor Control of Large Induction Motors by Neutralized Polyphase A-C. Commutator Machines*, by J. I. Hull, A. I. E. E. TRANS., 1920, Vol. 39, p. 1135.

"Three-phase Speed Regulating Sets with Separate Excitation," *E. T. Z.*, 47, p. 989, Aug. 26, 1926.

stalled at Devon, Conn., where they form a connection between the Connecticut Light & Power Company's 60-cycle system, and the New York, New Haven & Hartford Railway Company's 25-cycle system.

A wiring diagram of the Rochester 6000-kw. Scherbius-controlled, adjustable-ratio frequency converter set, is shown in Fig. 3. The equipment includes a main set, a regulating set, and auxiliary equipment. The main set consists of a 10-pole 7500-kv-a. three-phase 60-cycle 720-rev. per min. 11,000-volt, 80 per cent power factor synchronous unit, a 4-pole 8500-hp.,

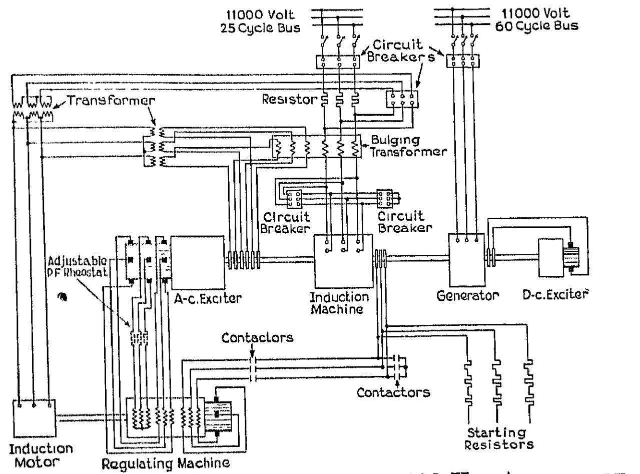


FIG. 3—DIAGRAM OF CONNECTIONS FOR A 6000-KW. ADJUSTABLE-RATIO INDUCTION-SYNCHRONOUS FREQUENCY CONVERTER

three-phase 25-cycle 11,000-volt, unity power factor induction machine, a 50-kw. 125-volt d-c. exciter, and a 7.5 kv-a. 25-volt a-c. exciter. The regulating set consists of a 475-hp. three-phase 25-cycle squirrel-cage induction motor, direct connected to a 300-kv-a. regulating machine which is a three-phase commutator type unit.

REGULATING MACHINE

The requirement of the regulating machine is to supply a voltage to the collector rings of the main induction unit, this voltage being at slip frequency and having a magnitude and phase angle controllable by the operator.

The construction of the regulating machine rotor is similar to that of a d-c. motor. Three sets of brushes on the commutator furnish the required three-phase voltage which is applied to the main induction motor rotor. As the regulating machine is completely neutralized, the current taken from the brushes on the commutator passes through a neutralizing winding on the stator which has the same effective number of turns as the rotor winding. In this way, the armature reaction is neutralized, the turns of the rotor and stator being opposed and balanced.

Due to the fact that it is sometimes considered difficult to obtain good commutation on a-c. commutator type machines, it is of interest to note that commutation on the regulating machine described is exceptionally good.

The regulating machine has the characteristic that whatever frequency is used in its excitation, voltage of that same frequency will appear at the armature terminals. Therefore for this application, it is necessary to furnish the regulating machine with excitation at slip frequency. Furthermore, means must be furnished for controlling the magnitude and phase angle of the excitation in order that the magnitude and phase angle of the armature voltage may be controlled. This required excitation is obtained from the a-c. exciter mounted on the shaft of the main set, as shown in Fig. 3.

A-C. EXCITER

Fig. 4 shows a close-up view of the a-c. exciter. The rotor of this unit has both collector rings and a commutator, and is similar in construction to the rotor of a rotary converter. Power is taken from the commutator through three sets of brushes spaced 120 electrical degrees apart. Means is provided for shifting the brushes, as will be described later. The stator punchings have neither slots nor windings, but provide a path for the revolving flux set up by the three-phase rotor current. The a-c. exciter is really a frequency-changing exciter, as it receives power at line frequency and converts it to slip frequency.

The energy taken from the commutator of the a-c. exciter is always at slip frequency for the following reasons: The a-c. exciter has the same number of poles as the main induction unit and is connected on the shaft of the main frequency converter. The collector

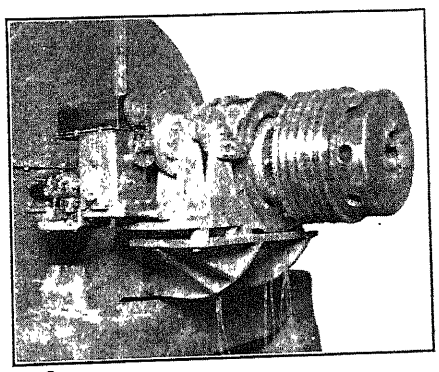


FIG. 4—A-C. EXCITER FOR A 6000-KW. ADJUSTABLE-RATIO FREQUENCY CONVERTER

rings on the a-c. exciter are connected to the same source of power as the stator of the main induction machine. The voltage supplied to the slip rings creates a magnetic field, which revolves at synchronous speed with respect to the a-c. exciter rotor. The direction of rotation of this magnetic field is opposite to the mechanical rotation of the exciter. The frequency of the voltage taken from the commutator is, therefore, determined by the speed of rotation of the magnetic field in space, and thus is always at slip frequency.

With the main motor running at exactly synchronous speed, the field of the a-c. exciter is stationary in space

and direct current is taken from its commutator. Under this condition, the regulating machine furnishes direct current to the induction unit secondary, as required for the operation of the latter at synchronous speed. With the induction machine running above or below synchronous speed, the magnetic field revolves in space at a speed that is the difference between the speed with respect to the exciter rotor and the mechanical speed; that is, at the speed of slip. Therefore, the voltage on the commutator of the a-c. exciter and on the commutator of the regulating machine is always of the same frequency as the secondary voltage of the main induction unit.

Control of Regulating Machine Voltage

Means of controlling the magnitude and phase angle of the voltage taken from the commutator of the regulating machine will next be discussed:

By reference to diagram of connections shown in Fig. 3, it will be noted that the regulating machine has two fields, one, the load field, and the other, the power factor field. Both of these fields are connected to brushes on the a-c. exciter commutator.

The load field of the regulating machine is connected to two sets of brushes on the a-c. exciter commutator, as shown in Fig. 3. By shifting these two sets of brushes in opposite directions, the brushes are permitted to span a greater or less number of commutator bars, thereby furnishing the means of obtaining variable voltage for exciting the load field of the regulating machine. This brush-shifting mechanism is motor-operated, so the brushes may be shifted either automatically, or by the operator. The movement of the brush-shifting on this exciter not only shifts the brushes to include more or less commutator bars but the two brush yokes are shifted in such a manner that the axis of the brushes is shifted.

The shift of axis changes the phase angle of the a-c. exciter commutator voltage. This compensates for the phase angle shift in the regulating machine load field excitation voltage which varies with change in slip frequency. This compensation is necessary in order that the phase angle of the voltage taken from the commutator of the regulating machine will not vary with change of excitation on its load field.

Power factor correction is furnished by the main induction machine supplying a quadrature component of voltage in its secondary circuit. This quadrature component is obtained from the armature of the regulating machine by exciting its power factor field from a third set of brushes located on the commutator of the a-c. exciter. See Fig. 3. This third set of brushes is stationary. The amount of excitation supplied to the power factor field is controlled by adjustment of the rheostat connected in the circuit. The power factor field of the regulating machine is connected Y. Due to the fact that voltage exists at all times across the stationary brushes on the commutator of the a-c. exciter, the power factor may be corrected or adjusted at a time when the main induction machine is operating at its natural slip, that is when zero voltage is impressed across the load field of the regulating machine.

By use of a series or so-called "bulging transformer," as shown in Fig. 3, automatic power-factor correction is obtained to compensate for the change in wattless kilovolt amperes that would ordinarily occur on the induction machine with change in load. The primary of this series transformer is connected in the primary circuit of the main induction machine and the secondary is connected in the a-c. exciter power supply circuit. This secondary winding introduces a voltage in the a-c. exciter circuit which varies with load on the main induction machine and is out of phase with the voltage obtained from the power supply.

Operating Characteristics

When the speed of the synchronous machine corresponds to the natural slip of the induction machine

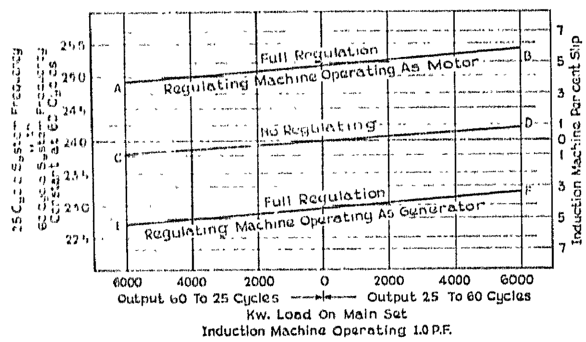


Fig. 5—Operating Characteristics of a 6000-Kw. Adjustable-Ratio Frequency Converter

at the required torque, no voltage is required from the regulating machine. If the speed corresponds to any other than the natural slip, output is required from the regulating machine, as shown by Fig. 5. This figure shows the output of the regulating machine for different combinations of slip on the induction machine and unity power-factor load on the main induction unit. The ordinates are calibrated in two different ways, the scale at the right indicating the slip of the main induction machine, and the scale at the left indicating the 25-cycle system frequency, under the condition that the 60-cycle system frequency is constant at 60 cycles. Line *C D* shows the natural slip of the induction machine when operating non-regulating, *i. e.*, with zero voltage across the main induction motor collector rings. Limits of load and slip are given by line *A B*, which shows full output of the regulating machine operating as a motor. Line *E F* shows limits of operation when the regulating machine is operating full output as a generator. Lines drawn vertically on the chart indicate operation with constant kw. load transfer through the main set. Points on any such vertical line show how output on the regulating machine

varies with change in slip, while kw. load on the main set is held constant. Lines drawn horizontally indicate operation with constant slip. Points on any such horizontal line show how output on the regulating machine varies with change in load on main set, while the relative frequencies on the two systems are held constant.

When the regulating machine is operating as a motor, the secondary power that would be lost in the resistor method, is transferred through the regulating set back into the line. When the regulating machine is operating as a generator, power is taken from the machine lines and transferred through the regulating set to the rotor of the induction machine.

Load Control

Load on the 6000-kw. adjustable-ratio frequency converter described may be held either by hand, or automatically. When under hand control, the operator changes load on the set by making use of a control switch on the switchboard panel. This control switch is connected to the small motor, which shifts the brushes on the a-c. exciter commutator. For automatic load

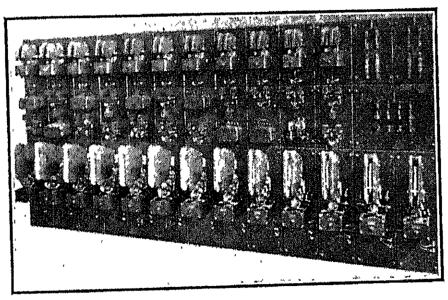


Fig. 6—Automatic Control Panel for a 6000-Kw. Adjustable-Ratio Frequency Converter

control, a load relay is provided, which may be set to hold any load desired within the operating range. The load setting is changed by turning a small dial on the face of the relay.

The relay has a wattmeter element and a floating contact, which moves between two stationary contacts. If the frequency ratio changes to increase the load on the set above the relay setting, the relay contacts will close, and automatically shift the brushes on the a-c. exciter and bring the load back to the desired value. If the frequency changes to reduce the load on the set, the relay contacts close in the opposite direction, causing the a-c. exciter brushes to shift to bring the load back to normal again.

Starting

Control equipment is furnished which permits automatic starting of the set from the 25-cycle end. The operator starts the sequence of operation by merely pulling a control switch located on the switchboard. Fig. 6 shows the starting panel, with the contactors and relays furnished with one of the Rochester sets. The regulating set and then the main set is automatically brought up to speed. The main induction motor is started with the primary winding connected Y and is later changed over to delta connection. Resistors for starting purposes are automatically connected in the main induction motor secondary circuit, and are later cut out, a step at a time. To reduce the inrush of current to the induction machine and also to reduce the induced secondary voltage at starting, resistors are inserted in the primary circuit, momentarily. After both sets are up to speed, contactors connect the armature of the regulating machine to the rotor of the induction machine. By use of a control switch on the switchboard, the operator can then shift the brushes on the a-c. exciter, to change the speed of the set as required for synchronizing the 60-cycle generator with the 60-cycle system. After the synchronizing has been accomplished, load is transferred through the set in either direction, as desired, by either hand-control or automatic-load-control.

Protective Features

Protective features are provided against a-c. undervoltage, over-speed, over-load, and excessive bearing temperature, and insure that the a-c. exciter commutator brushes are in the neutral position before starting.

The other 6000-kw. frequency-converter sets are very similar to the Rochester 6000-kw. set which has been described in considerable detail. The principal differences in the Altmar and Falconer 6000-kw. sets are their increased frequency range, and the provision for increased power-factor correction in the 25-cycle equipment. In the latter two sets the frequency range was increased 18 per cent, and the power factor of the main induction machine changed from unity to 95 per cent leading. In order to take care of this, the capacity of the regulating equipment was increased, the regulating machine itself being increased in capacity from 300 to 520 kilovolt amperes. With this arrangement, the 25-cycle induction machine can furnish leading current corresponding to approximately 2000 reactive kv-a. to the 25-cycle system over its entire load and frequency range.

The Devon 5000-kw. sets are different in several details from the 6000-kw. sets described. Ordinarily, it would be better to have the induction machine on the low-frequency end of the set, but in this case, a single-phase, 25-cycle machine was required, so it was necessary to place the induction machine on the 60-cycle end of the set. Also, in this case, the regulating machine is connected to the shaft of the main set, which makes an economical arrangement. Furthermore, on this unit provision is made for automatic power-factor control, as well as automatic load control, so the bulging transformers were omitted. Further simplification was made in the Devon sets by omitting the third set of stationary brushes on the commutator of the a-c. exciter, and exciting the power factor field of the regulating machine from one of the sets of

movable brushes. Also, in this case, no resistor was furnished in the primary circuit of the main induction machine, because of the lower induced secondary voltage in this unit.

The regulating machines furnished with the 5000-kw. Devon sets have a capacity of 500-kv-a. which is almost as much as the capacity of the regulating machine furnished with the 6000-kw. Altmar sets. However, the Devon regulating equipment is not used for power-factor correction to any great extent but rather to provide an increased range in the frequency regulation.

The regulating equipment is designed to raise the power factor of the induction machine to 90 per cent lagging and to furnish sufficient frequency regulation that the frequency of each system may vary 3 per cent either way, the worse case being when one system is 3 per cent high and the other 3 per cent low.

The main units of the Devon sets have different pole and speed combinations than the main units of the 6000-kw. sets, although the sets in each case connect 60- and 25-cycle systems. With the 6000-kw. sets, the 25-cycle unit has four poles, the 60-cycle unit 10 poles, and the normal speed of the 60-cycle synchronous unit is 720 rev. per min. With the Devon sets, the 25-cycle unit has 6 poles, the 60-cycle unit 14 poles, and the normal speed of the 25-cycle synchronous machine is 500 rev. per min. The Devon set was designed for less speed principally because of the more economical construction of the single-phase, 25-cycle synchronous unit that could be used. This lower speed also permits a saving in the capacity of regulating equipment. The most economical speed for the main set, as far as the regulating equipment is concerned, is 300 rev. per min., because at this speed, the 25- and 60-cycle synchronous speeds coincide, and less regulating is required for frequency variations away from 25 and 60 cycles. However, for the 5000- and 6000-kw. sets, the main units were not designed for 300 rev. per min., because the saving in the cost of the regulating equipment would be more than offset by the increased cost of the main units.

Fixed Ratio Induction-Synchronous Type

A paper[3] has been written which covers in much detail the design, theory, and operation of the fixed-ratio induction-synchronous type of set; therefore, only a very brief description will be given at this time.

Fig. 7 shows a diagram of connections for a 35,000-kw. set, which consists of an induction and a synchronous machine.

A portion of the power transfer is made through the shaft of the unit in the ordinary way and the remainder of the power transfer is made electromagnetically through the induction machine by connecting its stator to the 60-cycle system, and its rotor to the 25-cycle system.

3. *A 35,000 Kw. Induction Frequency Converter*, by O. E. Shirley, A. I. E. E. Trans., 1924, Vol. XLIII, p. 1011.

The induction machine has 14 poles and therefore a synchronous speed at 60 cycles of 514 rev. per min. However, its rotor speed is held down to 300 rev. per min. by the synchronous unit, this giving 25 cycles slip frequency at the induction machine collector rings. The electrical output of the induction machine rotor is approximately 25/60 of its kw. rating and the mechanical output of its rotor to the shaft of the synchronous unit is approximately 35/60 of its kw. rating.

Full load may be transferred through the set in either direction with unity power factor input. The magnetizing current of the induction machine is supplied through its rotor from the synchronous machine, which is designed to furnish the necessary reactive kv-a. for this purpose.

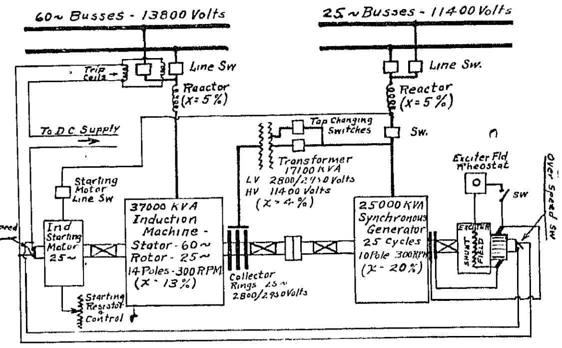


Fig. 7—Diagram of Connections for 35,000-Kw. Fixed-Ratio Induction-Synchronous Frequency Converter

Application

In discussing the application of the different frequency converters described, the synchronous-synchronous type will be used as a standard of comparison because this type is most widely used.

The induction-synchronous type of set has a rather limited field of application, being used principally to furnish power to small loads where the frequency required is different from the frequency of supply. Sets of this type in the smaller sizes are somewhat less expensive than sets of the synchronous-synchronous type but they have the disadvantage of poor efficiency and power factor. Furthermore, the induction machine cannot furnish leading current for power-factor correction, and the variation of frequency with change in load may be a handicap.

The fixed-ratio induction-synchronous type of frequency converter also has a limited field of application, its principal use being in large cities where synchronous converters supplied with a-c. power of two different frequencies are to be tied together on the d-c. side. With this type of set the two a-c. systems are tied together through the same magnetic field, therefore the tie functions practically as a cable tie, the only difference being that the impedance drop in the unit is somewhat higher than would ordinarily exist in a cable tie.

With a synchronous-synchronous set each machine tends to maintain voltage on the system to which it is connected, and a sudden drop of voltage due to a short circuit on one system does not in the first instant affect the voltage on the other system. The same is true in the case of a sudden phase shift in the system voltage due to a sudden load change. In either case, before any shock on one system can affect the other system the shock must be transmitted through the shaft and this requires time.

On the other hand the fixed-ratio type of frequency converter transmits such a shock instantly and causes a change of voltage on one system to affect the voltage on the other. In other words, the fixed ratio frequency converter ties the magnitude and phase of both systems and acts instantly, while the synchronous-synchronous type ties the phase only and requires time.

With the synchronous-synchronous type of set, a large voltage drop on one system may occur without affecting for the moment the other system. With synchronous converters of the two systems paralleled on the d-c. end, this voltage difference would cause large currents through the converters inverting those on the low voltage system. The fixed ratio type, however, would function in much the same manner as a cable tie allowing parallel operation of the synchronous converters under severe conditions.

The synchronous-synchronous type of set has some operating disadvantages as compared with the adjustable ratio type of frequency converter, but in the majority of cases these operating disadvantages are not sufficient to warrant the purchase of a more expensive set using the adjustable frequency ratio principle. Operating experience shows that in the majority of cases interconnected systems may be so operated that systems of different frequencies may be connected together by synchronous-synchronous frequency converters with no great inconvenience. In case of a system disturbance or system trouble, it may be desirable to disconnect the two systems and in such cases reserve generators are usually available to pick up any load that is dropped. The adjustable ratio frequency converters have the advantage that they may ride through system disturbances with less need of disconnecting the two systems. However, in deciding on the type of set to use in a particular case, it is necessary to decide how much the advantages given by the adjustable frequency converter set are worth. In general, it may be said that sets of the synchronous-synchronous type meet the operating requirements sufficiently well and have the advantage of lower cost, higher efficiency, and simplicity.

Although it is the general practise to use frequency converter sets of the synchronous-synchronous type, nevertheless there are particular applications in which the cost of an adjustable ratio frequency converter may be warranted. Frequency converters of this type are well adapted to connect large central station power systems to industrial or railway systems where the industrial load or railway load may cause considerable frequency fluctuations. Another application would cover cases where the extra cost of the adjustable frequency ratio type will be warranted from the standpoint of being able to control the load at the set itself without need of making adjustments on prime mover governors.

Chart Records

Chart records given in Figs. 8 and 9 show how well frequency converter sets of the adjustable ratio type operate during system disturbances. The changes in voltage and frequency of both systems interconnected and the kilowatt load transferred through the frequency converter sets are given. The charts in question were taken at Rochester in connection with the

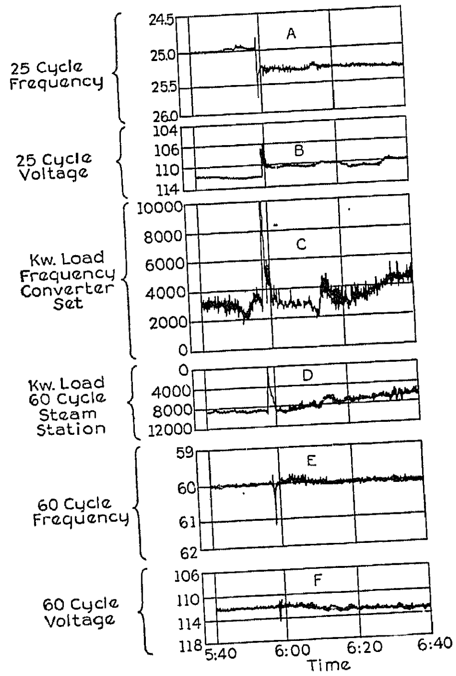


Fig. 8—Chart Records of a Disturbance Caused by Short-Circuit on 25-Cycle System

System tied to 60-cycle system by two 6000-kw. adjustable-ratio induction-synchronous frequency changers. Chart shows load on one set.

6000 kw. adjustable ratio frequency converter sets previously described.

In each case the system disturbance was caused by a short circuit on the 25-cycle system. It will be noted that the short circuits caused a dip in 25-cycle frequency and that the clearing of the short circuits accompanied by load reduction caused an increase in 25-cycle frequency. In Fig. 8 the 25-cycle frequency changed from 25 cycles to approximately 25.3 cycles where it continued to operate. The 60-cycle frequency after a momentary swing, continued to operate at approximately 60 cycles. This change in frequency ratio clearly shows the advantage of an adjustable ratio frequency converter.

At the time of the disturbance shown in Fig. 8, the 6000-kw. frequency converter sets were transferring

power from the 25- to the 60-cycle system, each carrying about 2500 kw. load (the chart shows only the load on one set). The increase in 25-cycle frequency to 25.3-cycles caused a sudden increase in power transferred through the sets as shown by 8-C. The sets were momentarily overloaded, the needle swinging to the end of the scale, showing the power exchanged was at least 10,000 kw. on each set. 8-C shows how the load relay operated and quickly reduced the load on the frequency converters back to normal.

8-D, 8-E, and 8-F show that the trouble originating on the 25-cycle system did not cause much disturbance on the 60-cycle system. The sudden increase in load on the frequency converter sets quickly reduced the load on the 60-cycle steam station as shown by 8-D.

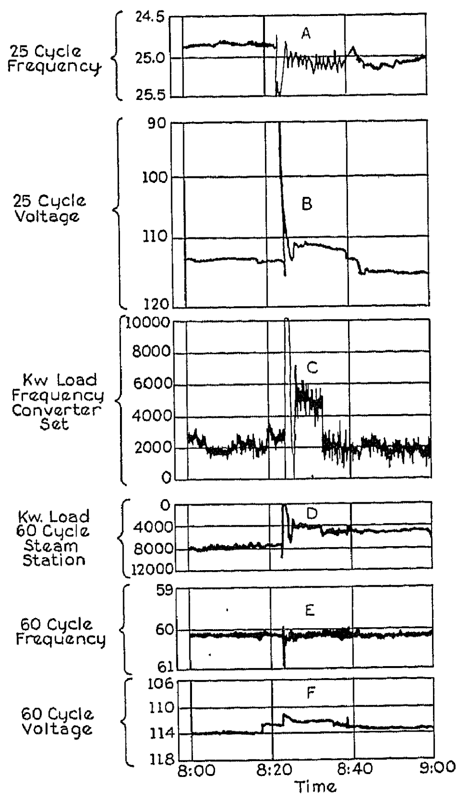


FIG. 9—CHART RECORDS OF A DISTURBANCE CAUSED BY A VERY SEVERE SHORT-CIRCUIT ON 25-CYCLE SYSTEM

System tied to 60-cycle system by two 6000-kw. adjustable-ratio induction-synchronous frequency changers. Chart shows load on one set

The disturbance recorded in Fig. 9 was much more severe than the disturbance recorded in Fig. 8. Here the 25-cycle voltage decreased momentarily to a very low value, the chart needle going off scale. In this case the 25-cycle frequency increased momentarily to approximately 25.5 cycles and remained at this high value for approximately 1½ min. As this large increase in 25-cycle frequency was out of the range for which the frequency converter was designed, the load relay and the load regulating device could not, during this period, reduce the overload on the set. This is shown by 9-C, the load through the set being such that the chart needle remained off scale until the 25-cycle frequency was again reduced. 9-D, 9-E, and 9-F show no great disturbance on the 60-cycle system during this period.

The fact that the adjustable ratio frequency converters rode through these disturbances as well as they did, speaks very well for their operation. The overload relays on the frequency converters were set for a little over double load. Therefore the disturbance recorded in Fig. 9 is about as severe a disturbance as the sets can handle without being tripped. It is very probable that a synchronous-synchronous set would have dropped out of step during the disturbances shown. With the synchronous-synchronous type of set a rise in 25-cycle frequency necessarily causes an equivalent rise in the 60-cycle frequency. Furthermore, during such system disturbances as shown, a synchronous-synchronous type of frequency converter would transfer more power through the set than a frequency converter of the adjustable ratio type.

GOVERNOR CHARACTERISTICS

The amount of load that is passed through a frequency converter when load is dropped on one of the systems to which it is connected depends to a large extent upon the governor characteristics and speed regulation of the prime movers. The speed regulation of steam turbines is much less than the speed regulation of water turbines; therefore, where the interconnected systems are supplied principally from steam stations there will be less interchange of power through frequency converters during disturbances than would be the case if the systems were supplied with power from hydro stations.

The author wishes to express his appreciation for the cooperation given by E. K. Huntington of the Rochester Gas & Electric Co. regarding the chart records described, and acknowledge the general assistance given by Messrs. J. I. Hull, P. W. Robinson, and O. E. Shirley.

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Discussion

INTERCONNECTION OF POWER AND RAILWAY TRACTION SYSTEM BY MEANS OF FREQUENCY CHANGERS

(ENCKE)

APPLICATION OF LARGE FREQUENCY CHANGERS TO POWER SYSTEMS

(BURNHAM)

NEW HAVEN, CONN., MAY 10, 1928

P. W. Robinson: Referring to Table IIB the guaranteed full-load efficiency of 86.9 per cent given for the Devon set proved to be a very conservative figure. Tests of the apparatus as built showed overall efficiency at full load ranging from 90.08 to 89.22 per cent at operating conditions varying from no speed regulation to maximum regulation. A comparison of specified and test efficiencies is as follows:

Load	½	1	1½
Specified	80.3	86.9	88.0
Test	83.0	89.2	90.6

Referring to Fig. 1, Mr. Encke has for simplicity disregarded the effect of reactance and primary resistance of the induction motor. It may be of interest to mention an important effect of the reactance when power-factor improvement is required, namely that of increasing the amount of flux and consequently the magnitude of the induced secondary voltage. For example, if the natural full-load power factor of the induction motor is 85 per cent with 25 per cent reactive drop and the regulating machine improves the power factor to unity, approximately 14 per cent more voltage is required from the regulating machine assuming that the same speed regulation is maintained. This is the major factor in determining the increased size of regulating machine required for power-factor correction.

There is also an increase in the secondary current required for anything more than a few points power-factor improvement but this is usually of practically negligible amount unless leading power factor is required. When improvement on the leading side is effected the size of the induction motor is likely to be increased as well as that of the regulating machine because not only are the core loss and secondary copper loss increased but also the primary copper loss, instead of decreasing as it does up to unity power factor, increases again.

Another rather interesting effect of the reactance is that, as load is applied to the induction motor, it retards the phase of the voltage required from the regulating machine. This phase shift calls for a change in the phase of the exciting current of the regulating machine as the load is varied. This change is effected in the Devon set by use of the automatic power-factor rheostat as explained by Mr. Encke and in some previous sets by use of bulging transformer.

Mr. Encke has mentioned that the interpole winding of the Scherbius machine at Devon is connected only for below synchronous operation. In explanation of this fact it may be noted that the required amount of speed regulation below synchronism is considerably greater than that above due to the fact that the synchronous speeds of the two main units are different while the specified frequency variations above and below normal are equal. This interpole winding produces interpole flux to set up a rotating voltage in the commutated coils in opposition to the voltage induced in them by the alternating field flux. It was considered advisable in this case to supply such interpole excitation for the higher flux frequency below synchronism but it is not needed above and would complicate the switching to provide it as the connections must be reversed. The ordinary interpole excitation for current reversal like that used in d-c. machines is supplied by extra bars in the compensating winding. By these two means it is theoretically possible in this type of machine to balance all voltages tending to produce sparking at the brushes. As may be observed the practical results attained in this case are almost complete absence of sparking under working conditions.

Referring to the adjustable-ratio induction-synchronous type of converter, the ordinary systems of exciting the regulating machine do not provide a means of building up and stabilizing the voltage on the induction unit to supply power to a "dead" system. Special schemes for excitation may be provided if required to accomplish such results. Unless reduced output is required for such conditions the scheme used should preferably provide for supplying low-frequency excitation rather than direct current to the rotor of the induction unit so that evenly distributed heating will be secured.

H. F. Brown: The question has been asked, why tie in a 25-cycle system with another 25-cycle system through a flexible variable-ratio frequency-changer set? There are five important reasons why this was done in the case of Station A.

The value of power interconnections is too obvious to comment on further. In order to connect together two systems of quite different sizes, it is of course necessary with the synchronous-synchronous set to observe certain proportions in the rated size of the set. The variable-ratio frequency-changer set can be any size within the limits of the smaller system. That of course is the first reason.

The second reason is because a railroad load naturally has a ragged peak characteristic. By means of this type set the swings are entirely eliminated from the smaller station.

Further, a single-phase railroad load such as the New Haven Railroad has produces an unbalance in the three-phase system as between phases at heavy loads. Taking it through this type of a set eliminates that tendency.

The single-phase railroad load such as the New Haven, is also lower in power factor than a system such as Station A supplying converters. The power factor of the smaller system is not affected and may be, in fact, improved on both systems by the use of such a set.

The fifth and last reason is the fact of the ability to ride through system disturbances. When it is considered that any railroad system of the size of the New Haven, may be subject to a large number of short circuits or line disturbances in a month, it will be realized that this is an important consideration. It is no reflection on the railroad system to have these disturbances, and the ability to continue operation and ride through them is one of the most important matters that engineers at present have been giving their attention to. The fact that we are able to carry a heavy railroad load through disturbances of this kind shows how this feature has been entirely put in the background as far as electric railroad operation is concerned.

O. E. Shirley: The papers have brought out the fact that there are three types of frequency converters available to interconnect two systems. It is sometimes possible by a very preliminary survey to determine the most suitable type, while in some cases it may be necessary to consider difference in initial cost, efficiency, and operating characteristics in considerable detail.

The selection of the variable-ratio type for the New Haven Railway converters, which have been described in these papers, could be made with practically no consideration of the other types.

The comparison of the variable-ratio converter with the other two types in ability to continue operation after severe disturbances may be explained by an analogy of springs. The fixed-ratio type may be considered as a short stiff spring, which will offer a rapidly increasing resistance to variations in frequency of either system, and will break before allowing much displacement. The machine of the fixed-ratio frequency converter with the lower synchronizing torque will fall out of step when its maximum capacity is reached, and it will then be necessary to resynchronize.

The variable-ratio set on the other hand may be compared to a longer spring which will yield much more for the same force. Disturbances tending to cause variations of frequency on one system, will, therefore, not cause an excessive load transfer through the variable-ratio frequency converter, and the load control will very quickly bring the load back to normal after the trouble is over.

These papers have also brought out two different types of regulating machines, one direct-connected or geared to the main units, and the other driven by an induction or synchronous machine which may operate either as motor or generator. There is no general rule for the choice between these types and the one to be used for any particular case must be determined for the size and speed for that case.

A. G. Oehler: I should like to know if this type of variable-ratio frequency converter has the same ability to cushion shock occurring on either end of the load, that is, when the shock is transferred in either direction?

L. W. Encke: Mr. P. W. Robinson mentions that factory tests made on the Devon sets showed overall efficiencies higher than those mentioned in the paper. The efficiencies of both types of sets given in the paper are values set forth in the specifications. After the installation of the machines, efficiency tests, made by metering the input and the output of the whole set, gave for the Devon sets about the same results as those found on the test floor, and for the Station A machines efficiency figures equal to those on the Devon sets.

Answering Mr. A. G. Oehler's question, it can be said that this type of variable-ratio frequency changer cushions shock occurring on either system. Furthermore, immediately after the disturbance is over, the lead-regulating equipment restores normal load conditions on the set.

E. J. Burnham: In Mr. Robinson's discussion he mentioned the need of building up and stabilizing the voltage on the induction unit of variable ratio sets.

In supplying sets of this type we have always stated that sufficient generating power should at all times be connected to the induction unit to stabilize the frequency on the induction end of the set.

By referring to the diagram of connections it will be noted that excitation to the regulating machine comes through the a-c. exciter from the main line. Generating power should therefore be connected to the main line to furnish the required excitation. This generating power is needed to build up and stabilize the voltage on the induction unit when the set is started and it is also needed to stabilize the voltage and frequency during operation of the set.

At the Rochester Station, all the generating power was dropped from the 25-cycle induction end of the set momentarily to see if the set would hold its 25-cycle frequency, and it was found that the frequency did hold somewhat stable for a very brief time. I feel that it would not necessarily continue at this point of stability if dropping of load or fluctuations would take place on the system.

The variable-ratio type of sets now in operation have not been required to furnish power to a dead load from the induction unit; therefore special means of excitation to build up and stabilize the voltage on the induction unit have not been needed.

In case it should be required that the induction machine furnish power to a "dead" system, then special means of building up and stabilizing the voltage would be required. This could easily be furnished by use of a small motor-generator set which would furnish a-c. power at the desired frequency and voltage to the collector rings of the a-c. exciter.

Replying to Mr. Oehler's question, I might state that the variable-ratio type of frequency converter forms a flexible tie between the two systems so that shocks are cushioned as they pass through the set no matter which system receives the original shock.

The Chicago Terminal Electrification
of the Illinois Central Railroad

BY R. F. SCHUCHARDT[1] and W. M. VANDERSLUIS[2]

Fellow, A. I. E. E. Associate, A. I. E. E.

INTRODUCTION

THE development of transportation, using the term in its generic sense, is a measure of the progress of civilization. This includes transportation of material things, as done by vehicles, ships, railroads, and air-ships; transportation of energy from hydro and steam generating stations to the user; transportation of thought by telephone, telegraph, and radio; and now, the transportation of views by television. Transportation reduces time and distance and increases man's range of activities. Communities thrive to the extent to which their transportation facilities are developed.

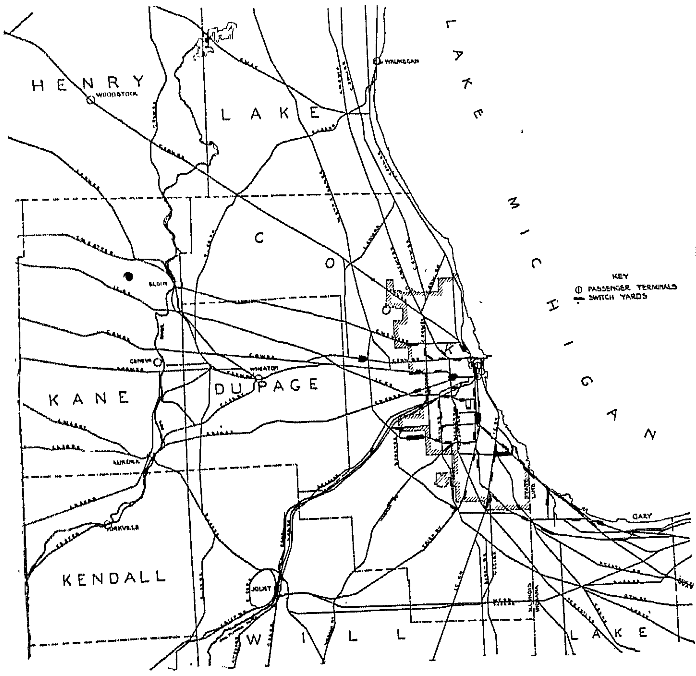

FIG. 1—RAILROADS IN CHICAGO REGION

Chicago enjoys the distinction of having the most extensive railroad facilities in the world. Its local street and elevated car systems are in the front ranks, as is also its electric power development; and its communication system is on a par with the best. This is not said in a spirit of boasting, but to give point to the statement that the methods used to solve the physical problems of that city are of interest to all progressive individuals, and particularly to engineers, since engineering is so much the basis of present-day progress.

In this is found our justification for accepting the invitation to present at this eastern Regional Meeting, a description and discussion of the first electrification of steam railroads to be put into service in the midwestern metropolis.

Let us first try to get a rough picture of the general local railroad situation. Downtown Chicago is served by 21 roads, though only 8 of these reach the central zone over their own track. (Fig. 1.) In the metropolitan area of 1750 sq. mi., there is a population of four million. There are 7726 mi. of railroad trackage and 4330 industries on railroad sidings. Six and one-quarter per cent of all freight in the United States (or 11,400 cars daily) are unloaded here and 4½ per cent are loaded. Nearly 35,000 freight cars are operated daily with a car mileage of over 1,150,000. An average of ten and one-half cars arrive, and the same number depart each minute.

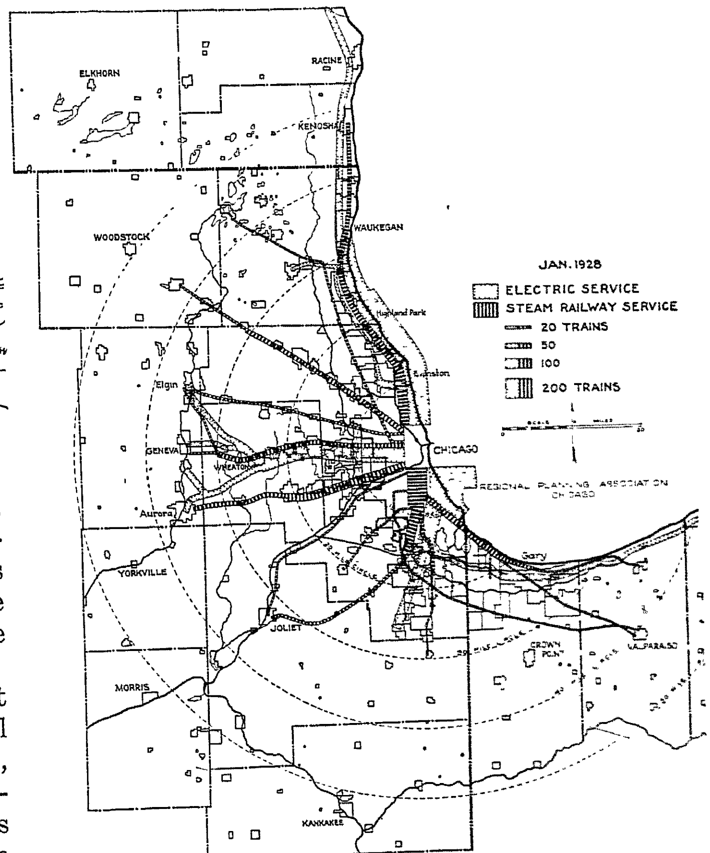

FIG 2—NUMBER OF RAILWAY COMMUTING TRAINS DAILY IN CHICAGO REGION—BOTH DIRECTIONS

In the passenger service, there are over 500 through trains carrying 45,000 passengers and about 1100 suburban trains, carrying 300,000 passengers, arriving and departing from the terminal stations daily. (Fig. 2.)

These figures[3] will help you to visualize the great

1. Elec. Engr., Commonwealth Edison Co.

2. Elec. Engr., Illinois Central R. R., Chicago.

Presented at the Northeastern District Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

3. Freight data based on 1927 Report of the Committee on Coordination of Chicago Terminals, representing 28 roads. Passenger data estimated from 1923 survey data by same Committee.

system of transportation centering in the Chicago region.

With the continued growth of the city and the further expansion of railroad facilities, it seemed inevitable that some day many of the roads would be led to consider electrification of their terminal areas because of congestion, or for other compelling reasons. In anticipation of this time, and with a thorough appreciation of the economy to the community in having the necessary power supply taken from the existing central station system, in 1921 Mr. Samuel Insull, president of the Commonwealth Edison Company, appointed a committee to study the problem. It was Mr. Insull's desire that his engineers be well posted on railroad points of view and railroad operating requirements, so that in subsequent negotiations, the power men could better understand railroad language and railroad needs.

The Committee for the Study of Railroad Electrification, as it was called, was headed by Mr. Britton I. Budd, president of the Public Service Company of Northern Illinois, of the Chicago Rapid Transit Company, and of the Chicago, North Shore, and Milwaukee Electric Railroad. Its membership was drawn from the electric roads under the Insull management, as well as from the local electricity supply companies of the region. This insured a fuller understanding of transportation problems.

The committee met regularly each week for nearly a year, and also visited practically all of the steam road electrifications in the country. Greatest courtesy was extended the members by the officials of all of the roads visited, and facilities to study operating data and view the system in great detail, (including repair shops) were offered freely. In addition, railroad officials and representatives of equipment manufacturers were invited, and came to the committee's meetings to give valuable information on the subject.

That the committee obtained at least a partial insight into railroad problems is reflected in its conclusions, some of which are given in the following excerpt from its notes:

"In negotiations with railroads for the supply of energy to electrified systems, it is necessary for the power company to give full consideration to certain features of railroad operation which affect the use of this energy. Briefly, they are as follows:

"Present railroad operation is based on the performance of steam locomotives and will, naturally,—at least for the present,—be adhered to when a road is electrified. A steam locomotive is a self-contained unit and is not affected by the disability of other locomotives except as the track may be obstructed thereby. The total power available to the railroad at any time is therefore the sum total of all the locomotives in good condition. Train movements are thus limited only by the number of locomotives available and the track capacity. Electric service must approximate this condition as closely as possible. Energy to move trains as per schedule must at all times be available and interruptions very carefully guarded against. In emergencies, excessive amounts of energy may be required and the limit of the free capacity in station, lines, and substations should be available to the railroad.

"The contract should recognize the above requirements and should also express in its rates, terms, and conditions, the superiority of central station service from the railroad's point of view. The contract should reflect the fact that the cost of energy from a general power supply system is less than that from a properly designed separate station of the railroad, and that the service from such a general supply system is more reliable. The fact of the larger reservoir for emergency use afforded by a general supply system is one of the principal advantages of such supply and the contract must be so drawn that the railroad can make use of this advantage without paying an unduly heavy charge for such use. The railroads, on the other hand, should have it clearly pointed out to them that while this reservoir is very much larger than it would be if they had stations of their own, there are still limitations which are usually in line and substation capacity rather than in generating station. Excess reserve in any of these items will naturally require a larger primary charge, since additional investment must be made for the purpose. In drawing the contract, clauses covering emergency energy,- real operating emergencies, such as those caused by accidents, should be differentiated from those due to unusually heavy traffic. The latter would have required additional steam locomotives for the steam road, and therefore an additional primary charge for electric service for this purpose is entirely proper."

At the time of the committee's studies, the Illinois Central Railroad was solving its terminal electrification problem. These studies naturally were in the nature of preparedness steps, looking toward readiness to offer intelligently power service for such electrification, should an invitation for such offer be forthcoming, as it was later.

All members of the committee studiously avoided divulging their separate or collective thoughts with reference to a choice of system for this electrification. The power company stood squarely on the policy of readiness to serve the railroad with power in any form it desired. The contract conditions for the service would necessarily be affected by the choice, but not the willingness to serve. When the railroad made its decision for 1500 volts, direct current, and invited proposals for power supply on the basis of high-voltage energy, (the railroad to do its own converting), or on any other basis if desired by the power company, the latter submitted with its proposal for high-voltage energy, an alternate based on delivery of energy ready for traction use. It was felt that the road would be served better if all essential parts of the power supply were looked after by men especially trained for that

work. This is also in harmony with the general interests of the community because of the better economy of joint use of part of the facilities for this and possible other electrifications and for light and general power service.

The Illinois Central Problem

The location of the Illinois Central tracks along the lake shore is not due to the railroad's wishes. It had no choice in the matter. When the city had grown large enough and wealthy enough to want the lake front for parks and boulevards, the railroad was in the way of these improvements, and it was necessary for some kind of an agreement to be reached between the city and the railroad company, involving the surrender of the company's riparian rights and an adjustment of other property in such a way that both the city and the railroad would benefit. For some years there was considerable agitation, also, in favor of the electrification of Illinois Central trains in order to eliminate the smoke which it was claimed detracted from the beauties of the lake front. An agreement was eventually reached between the city and the railroad by which all the desires of the city with regard to the improvements, particularly electrification, would be realized by stages, and by which the railroad, in turn, would receive certain benefits such as the acquisition of certain property rights and relief from the expense of protecting the lake front against erosion. This agreement is embodied in the so-called "Lake Front Ordinance."

On account of the diversity of ownership and of administrative powers of the various interests involved, it was necessary to make the agreement include the South Park Commissioners and also the Michigan Central Railroad. In addition, permission of the Secretary of War had to be obtained for certain of the lake front changes.

Under the ordinance, the railroad was obligated to electrify its complete suburban service by February 21, 1927. The electrification of the freight service north of Roosevelt Road must be completed by 1930, and south of Roosevelt Road by 1935. The electrification of the through passenger service must be accomplished by 1940, provided agreement is reached between the Illinois Central and its tenant railroads with respect to electrification.

The Illinois Central placed its suburban service in complete electric operation in July 1926, a full six months before the limit specified by the Lake Front Ordinance. In addition to the electrification, the railroad made many improvements, a large number of which were not required by the ordinance. These included extensive track changes, grade separations, yard construction, and other works.

The suburban service to be electrified was the most important means of rapid transportation serving the densely populated Hyde Park, Woodlawn, and South Shore districts, as well as the more outlying districts and suburbs directly south of the city. Because of its fast and frequent trains, it was considered the best transportation in the city, notwithstanding the fact that its coaches were old, small, and of wooden construction, and its locomotives equally small and old. The suburban system comprises 37.8 route miles, including 30 mi. on the main line and 8.8 mi. on two branches. There were three classes of trains; namely, local, express, and special. As many as six parallel tracks were necessary in the heavy traffic districts. In the year 1922, when definite plans for the electrification were begun, 21,500,000 revenue passengers were carried by these steam trains.

Special Commission Appointed to Study the Problem

In order that this electrification might be along the most progressive lines, the railroad employed three noted electric railway engineers as an Electrification Commission to make an extensive detailed study of the requirements and a selection of the best system to fit these requirements. This Commission was aided by a staff of engineers employed by the railroad company for this purpose. In reaching its conclusion, the Electrification Commission made designs and estimates of the complete costs of electrification of the terminal by each of four different systems. Two years were consumed in this study, and in the autumn of 1921, the report was submitted recommending the 1500-volt d-c. system as the one best suited to this terminal electrification.

With the selection of this system, the Commission's work was ended. The railroad then gathered a force of engineers to design and construct the electrification. In the course of the design, numerous decisions had to be made, involving extensive studies and investigations.

Studies of the Power Supply

Among the major studies that occupied the railroad's engineers was naturally that of the most satisfactory power supply, all things considered. Extensive and careful estimates were made to determine what the power costs would be if the railroad owned and operated its entire power system. These estimates were then compared with the proposals of the power company. In the decision, of course, these cost figures were fully considered, but the operating advantages of obtaining energy from a large centralized power system, and of having the power company perform the operations to provide the energy in the form needed for transportation service also carried weight. As a result of these studies, which were carried on over many months, the railroad concluded to purchase all of its electric energy from the power company.

Fundamentals of the Power Contract

The contract which was entered into in 1924, and under which operations commenced in May 1926, calls for the delivery of energy from the substations of

the power company. This is at 1500 volts, direct current, on the feeders of the railroad company for traction and 2300 volts, alternating current, for signaling. Three-phase energy at 4000 volts is also provided for the railroad's light and power requirements in its stations and shops. The present supply is taken from seven substations, five of which are within the city and two beyond the city limits (Fig. 3). From the two outside substations the power company supplies the energy by arrangement with the Public Service Company of Northern Illinois, which owns and operates these substations. This latter company, however, does not appear in the contract with the railroad company. The conversion equipment consists of synchronous converters and mercury arc rectifiers, which are described more fully below.

The charges for electricity follow the proved Hopkinson method with a "primary" in recognition of the power company's investment and a step rate "secondary" to cover the operating and service costs. In order that variations in coal cost may be taken into account, there is provision for a change in the secondary charges if the cost and heat content of the coal used falls outside of certain limits.

The primary charge is based on the maximum amount of electricity drawn under normal operating conditions. In order that the railroad company may have the advantage of the power company's large reservoir of power and without the payment of the regular primary charge for additions required in emergencies only, abnormal demands due to such emergencies are excluded in determining the maximum demand for billing. The recognized emergencies are:

1. Abnormally heavy traffic resulting from failure of other transportation lines, unless continuing for more than 10 consecutive days;
2. Traffic arising from extraordinary assemblages, such as fairs, race meets, ball games, conventions, and the like, unless continuing for more than 10 consecutive days;
3. Congestion of traffic arising from a railroad accident, derangement of power supply, or other emergency conditions;
4. Other excessive traffic beyond that usually carried and caused by some unusual circumstance or condition;
5. Hours during which the temperature is + 5 deg. fahr. or lower. (The suburban cars are all electrically heated.)

The limit to the amount of electricity which may be drawn under these emergencies is the capacity of the power company's equipment which may be usable for the railroad company's service during such emergencies. This is one of the features of the contract which makes the central station service of so much greater advantage to the railroad than would be that from its own separate plant. To insure a reasonable, continuing return on the investment made by the power company the railroad guarantees that the maximum demand that it will pay for in any month will not be less than 70 per cent of the highest demand established during the last preceding

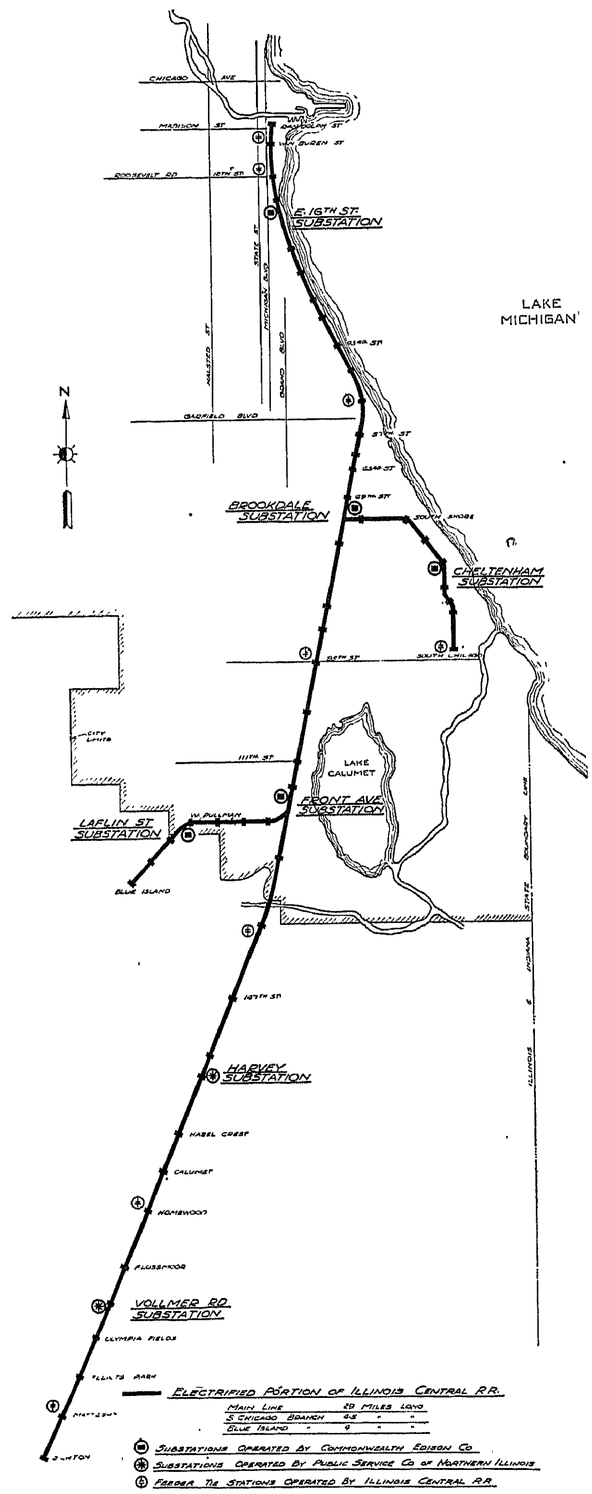

FIG. 3—ELECTRIFICATION OF ILLINOIS CENTRAL RAILROAD (SHOWING SUBSTATION)

12 months. A minimum monthly load factor of 30 per cent is also guaranteed.

One of the railroad's requirements which was finally accepted by the power company but with some mis-

givings, relates to regulation of the feeder pressure. The high-speed suburban service with short intervals between trains requires a close adherence to running schedule and this, in turn, was felt to demand close voltage regulation. The permitted variation is from 1400 to 1550 volts on the feeders at the point of delivery at the railroad's right of way, which is practically at the substation feeder bus.

Provision is included for additional capacity in new or existing substations, as the increase in load requires. Of course, the power company may install additional equipment in its substations for uses other than this

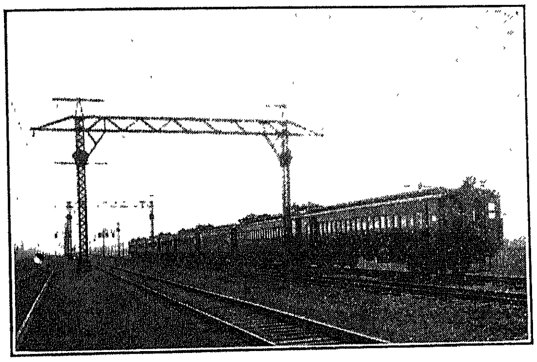

FIG. 4—8-CAR TRAIN AND CATENARY

electrified railroad, and also use its equipment to serve other electrifications later if found advantageous to do so.

DESCRIPTION OF ROLLING STOCK AND DISTRIBUTION SYSTEM

The suburban cars of the electrified suburban service are of the most modern all-steel type of rapid transit cars, although considerably faster and heavier than the average subway and elevated car. They have been fully described in the technical press[4] at various times, so a detailed description here is unnecessary. All the trains are made up of standard two-car units, each unit consisting of a motor car and a trailer car semi-permanently coupled. In seating capacity and general appearance the trailer car is exactly the same as the motor car. The two-car units can be operated from either end. They reach speeds of 65 miles per hour on level track. They have a very fast acceleration and braking rate, which allows them to make short runs with high-schedule speeds. The express trains and the fast trains serving the outlying districts, however, make long high-speed non-stop runs until they reach the territory they serve.

The trains obtain their energy from the catenary distribution system. (Fig. 4.) The catenary over each electrified track contains four conductors, two of which are contact wires. It is directly connected to the feeder busses of the substations. The conductivity of this arrangement is such that no feeders other than the direct connections between substation bus and this overhead contact system are used. Normally the overhead system is all tied together through the substations and tie station buses (Fig. 5). These stations are so located that in case of faults, the section in which the fault occurs will be automatically isolated. High-speed circuit breakers with good selectivity characteristics are used in all connections. A detailed description of the distribution system can also be found in technical publications.

THE SUBSTATIONS AND THEIR EQUIPMENT

The energy supply for the initial electrification is obtained through seven substations located adjacent to, or very near, the railroad right-of-way. Five of these are within the city and are fed from the generating stations at 12,000 volts, 60 cycles over the power company's cable system. The two substations in the suburban region are fed from the 33,000-volt, 60-cycle overhead transmission system of the Public Service Company of Northern Illinois. The line arrangement throughout is such as to provide reasonable reserve so as to insure a high order of reliability.

The major equipment installed in these substations is given in the Table. Figs. 6, 7, and 8 show the exterior of some of the substations.

The 1500 volts direct current for the traction service is derived in part through 3000-kw. synchronous converter units and, in part, through mercury arc rectifiers. Each converter unit consists of two 750-volt elements in series, together with a single-three-to-six-phase

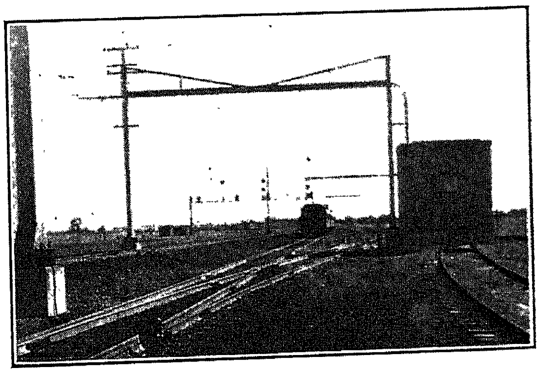

FIG. 5—FEEDER TIE STATION

transformer. The illustration (Fig. 9) of a converter unit in the Brookdale Substation shows the flash suppressors around the commutator brushes. Another, and principal precaution against possible flashovers at the commutators is in the use of high-speed circuit breakers.

The converters are designed to carry 150 per cent rated load for two hours and 300 per cent for one minute with satisfactory commutation. They are of the field-control type where d-c. voltage control is obtained by varying the excitation, thus regulating by means of the reactive current thereby produced.

4. Quite fully in *General Electric Review*, April, 1927.

TABLE I
MAJOR SUBSTATION EQUIPMENT

Substation	Synchronous converters		Rectifiers		Total kw. capacity	1500-volt feeders		Light and power transformer capacity
	No.	Rated kw. capacity	No.	Rated kw. capacity		Pos.	Neg.	
E. 16th St.	3	3,000	0		9,000	7	6	1,500
Brookdale	2	3,000	1	3,000	9,000	10	9	1,500
Cheltenham	2	3,000	0		6,000	4	2	150
Front	2	3,000	0		6,000	7	6	300
Laflin	0		1	1,500	1,500	2	1	75
Harvey	1	3,000	1	2,000	6,000	4	1	300
Vollmer Rd.	1	3,000	1	1,500	4,500	4	1	300
Totals	11	33,000	4	9,000	42,000	38	26	4.125

The exciter for each converter, mounted on the shaft of one element, is compound wound for constant voltage and the variation in the converter field voltage is automatically obtained by means of a counter e. m. f. regulating equipment. The converters are started from the a-c. side by means of the usual star-delta switches.

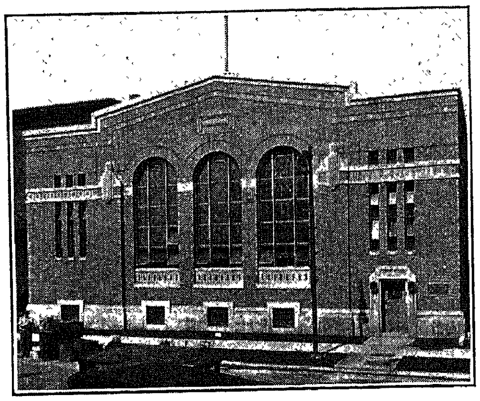

FIG. 6—16TH STREET SUBSTATION

A further means of voltage control is provided in the primary winding of the transformer. By means of interlocked oil switches, the connection may be changed under load from the full coil to a 5 per cent tap. Automatic reclosing is provided for the high-speed breaker on the negative lead of the converter with a time delay, which will reclose if the short circuit clears; but if it fails to clear, the positive breaker will also open. This, too, is of the high-speed type.

There are four rectifiers in this service, their location being shown in the table. Two of them, of 3000-kw. capacity, are of foreign manufacture and the other two, rated at 1500-kw. each, are of American make. Both of the 1500-kw. and the 3000-kw. units consist of two bowls each, operating in parallel. A single three-phase transformer with six-phase secondary windings feeds the pair of bowls of the 1500-kw. sets. The 3000-kw. sets are in effect, two 1500-kw. sets operated from one high-voltage switch. Each bowl has its own three-phase transformer. The secondaries are double six-phase connected to the twelve anodes of the bowl. (Figs. 10 and 11.)

These rectifiers are rated to carry 150 per cent load for 20 minutes and 300 per cent load momentarily (American units) or for one minute (foreign units). High-speed circuit breakers (Fig. 12) are provided on the d-c. side of these units. Special reactance coils connected in the neutral of the transformer secondary give the sets an inherent regulation of about 5 per cent. Corrective regulation is accomplished by hand-controlled tap changers on the transformer primary.

All of the 1500-volt feeders have a high-speed circuit breaker on their positive side.

In addition to this equipment for the traction service, each substation contains transformers with regulating and switching equipment for 4000/2300-volt, three-phase light and power circuits for the railroad and for 2300-volt signal service.

To insure safety and reliability, the substations contain a number of interesting features but a detailed description of these would belong to another paper.

OPERATING EXPERIENCE

This electrification has now been in operation for 21 months. From every point of view the equipment has met all expectations, and the complete operation has apparently been successful. The first electric time

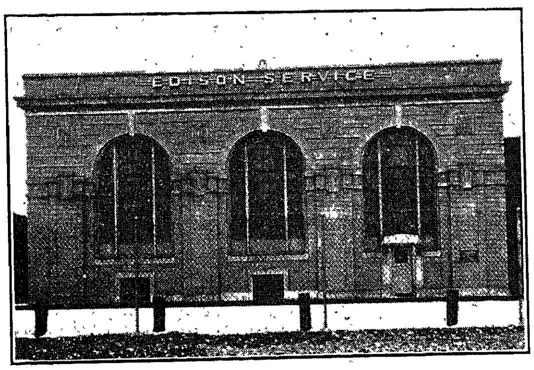

FIG. 7—BROOKDALE SUBSTATION

table was put into effect on August 28, 1926, with a total of 396 revenue trains. Today, 497 trains are being operated on a normal week day. There are 72 additional electric trains run by the Chicago South Shore and South Bend Railroad, which uses the Illinois Central electrified tracks between 116th Street and Randolph Street, making a total of 569 electric trains

on every week day. The public has shown its appreciation of the electrification by the increased traffic, even though the fares were raised 20 per cent a few months before electrification started.

Fig. 13 shows graphically the increase in revenue passengers from January 1924 to February 1928, and the effect of the electrification is plainly seen. On this graph are also shown the car miles, the seat miles, and the number of daily trains. It may be noted that the

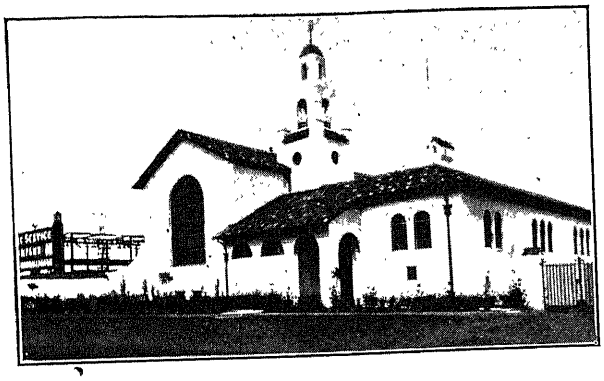

FIG. 8—VOLLMER ROAD SUBSTATION

car miles did not increase very much after electrification, this being due to the fact that the seating capacity of the new electric car is one-third greater than the average old steam suburban car and the standing capacity is increased still more.

The operation has not been entirely free from troubles but that cannot be expected from an installation of the magnitude of this electrification. However, they have not been of a major character and with one or two

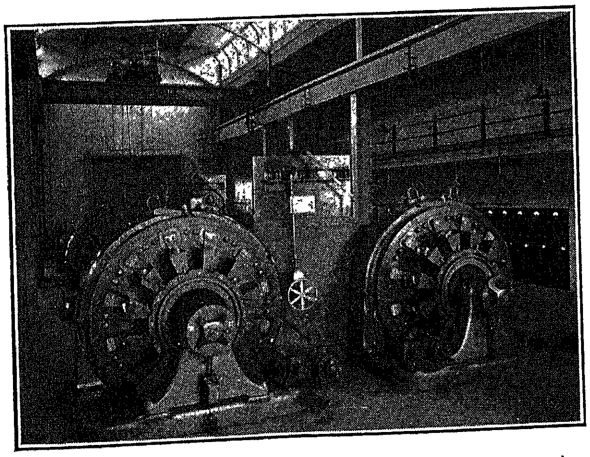

FIG. 9—SYNCHRONOUS CONVERTERS (BROOKDALE)

exceptions, have not interfered with the transportation service.

The operation of this service depends on an adequate and reliable supply of energy. While the Electric Service Agreement between the power company and the railroad company calls for a practically continuous supply of energy, both companies must at all times cooperate very fully in order to maintain efficient service, on account of the electric switching operations involved and because of common maintenance troubles inevitably arising. Such cooperation has been complete in every way, and all routine and emergency arrangements for continuity of service have been handled with efficiency and satisfaction.

Fig. 14 shows the magnitudes and variations of maximum power demand of this suburban service, the load factor, and the kw-hr. per car mile, all mea-

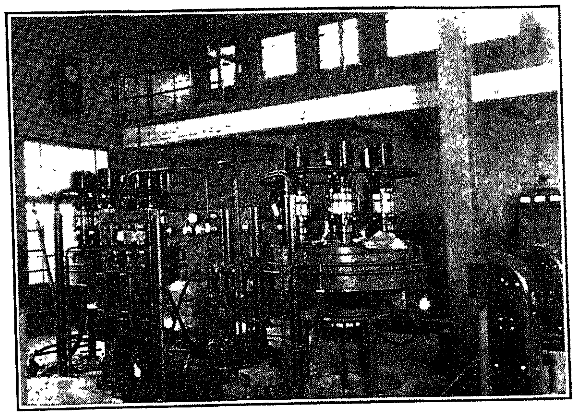

FIG. 10—MERCURY ARC RECTIFIERS (LAFLIN)

sured at the d-c. bus in the substations. The relation of these values to mean monthly temperature can be observed. The fact that the cars are heated entirely by electricity makes the temperature an important influence.

Because of the heavy load fluctuations imposed on the substation converting equipment and of the close regulation specified by the railroad, there was doubt in

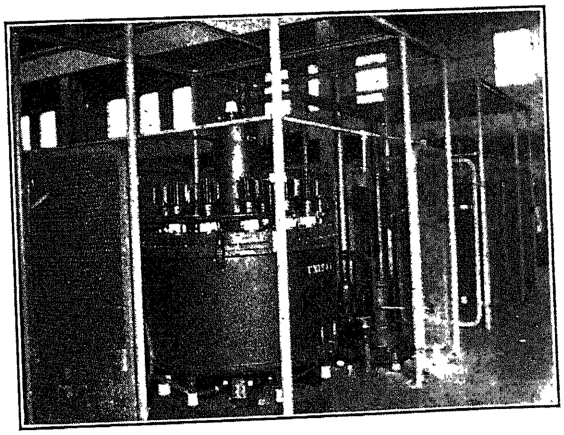

FIG. 11—MERCURY ARC RECTIFIERS (BROOKDALE)

some quarters that synchronous converters would give satisfactory service and motor generators were suggested. Fortunately these doubts have proved groundless, the performance of the converters having come fully up to requirements.

The rectifiers also, in general, have performed well,—particularly those of foreign manufacture. In the others, some improvements are still desirable and it is hoped that our American manufacturers will not permit

themselves to be outdone for long. Because of the higher efficiency of rectifiers, they are naturally kept on the service for the long hour load. The close regulation is performed by the synchronous converters. As already stated, the exacting regulation specified has been met satisfactorily.

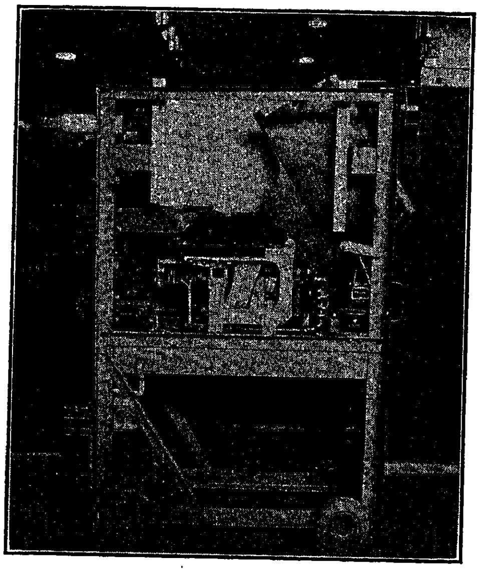

FIG. 12—HIGH-SPEED CIRCUIT BREAKER (WITH ASBESTOS CHUTE TILTED BACK)

That very important link, without which the major equipment would not perform so satisfactorily,—namely, the high-speed circuit breaker,—has done all that was expected of it. Both in correct selectiveness and in effective current interruption its behavior has been excellent. The duty on these devices is at times

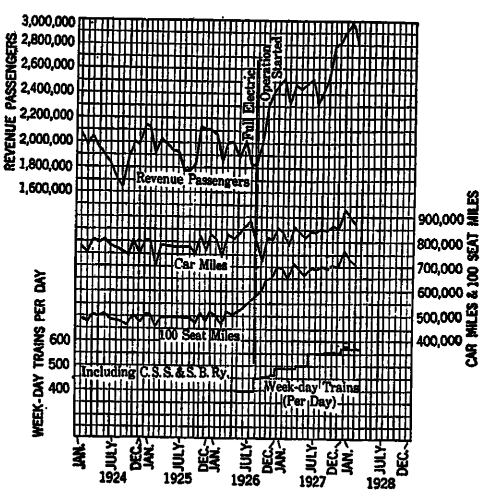

FIG. 13—TRAFFIC DATA

heavy. They have effectively limited to a negligible degree the damage resulting from accidental short circuits in overhead wires or rolling stock.

POWER DATA

The maximum demand of the electrified road on the power system has thus far been approximately 24,000 kw. The total 1927 energy use was slightly under 59,000,000 kw-hr. The annual load factor was thus about 28 per cent. The monthly load factor varied from 32½ per cent to over 39 per cent.

At the time of the power companies' maximum load this last winter, the railroad's load was about 7 per cent lower than it was at the time of its maximum, which occurred a week earlier. It should be noted that this diversity existed even though the portion of the road

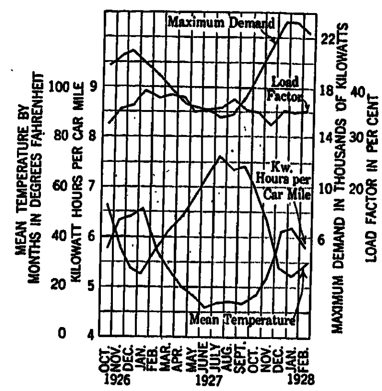

FIG. 14—POWER DATA

thus far electrified—suburban service, only, in winter has a daily load characteristic which closely approximates that of the power company. With the addition of the freight and of the through passenger service, this diversity should be much higher.

The increased business that the railroad has enjoyed since electric operation was begun has shown the inadequacy of the estimates originally made with reference to probable power requirements when the

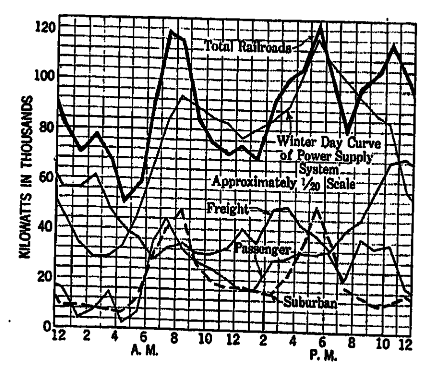

FIG. 15—ESTIMATED LOAD CURVE FOR 1928 FOR ALL RAILROADS IN CHICAGO ASSUMING THEM TO BE COMPLETELY ELECTRIFIED

other branches of its service are added. The revised estimates have not yet been completed.

The power company has made some rough estimates with reference to the entire Chicago railroad service, which are given in Fig. 15. This shows the shape of the daily load curve for a winter day. Superimposed on these curves is a typical curve of the regional power system load (but to a different scale). The combined railroad load is estimated to have an annual load factor of about 62 per cent. Further improvement may

be possible by shifting freight time tables. From the power company's point of view, this is a very desirable load. The railroads, on their part, receiving their supply from the large power pool, would enjoy, among other things, the advantages of the high generating efficiency of the rapidly growing system, the comparatively large reserve, and the absence of heavy capital requirements for power purposes.

The estimated maximum demand for 1928 for all the railroads in the Chicago region, were they electrified, is on the order of 125,000 kw. This is but a little over 8 per cent of the interconnected generating capacity of the region; actually less than the single item of reserve normally carried by the power companies. Two points are brought out by these figures: (a) that the investment necessary to provide the power requirements of electrified railroad business is not a burdensome item in the power company's budget, and (b) that the particular form of energy required by the railroad will not have any appreciable influence on the general engineering plan of the power company.

While these conclusions are based on the conditions existing in the Chicago region, they will probably be found to apply with at least equal force elsewhere. The ever enlarging area being covered by substantial power systems with their far flung transmissions is constantly increasing the ease of obtaining a suitable supply of energy for railroad electrifications, as the railroads find, with the progress of time, that economic or other conditions make electrification desirable. Power systems will serve the railroads most effectively when there is a willingness to serve in the manner demanded so that the railroads in turn can produce their service as best suits the requirements of good transportation.

Discussion

E. R. Hill: One of the very interesting and important features of the Illinois Central Electrification, as described in this paper, is the contract for the supply of power between the Railroad and the Commonwealth Edison Company. Probably the most unusual feature of this contract is the supply by the power company of converted current at the seven substations located along the railroad. It is more usual for the power company to supply alternating current at a single point and for the railroad to transmit and convert or transform this power itself.

The paper calls attention to the practise which has now become quite general, and which is regarded as absolutely essential in connection with railroad electrification work, for the power company to supply excess demands in railroad emergencies without affecting the demand charge. In other words, the demand charge is determined by the road's power requirements under normal conditions, and emergency drafts of power do not affect the demand billing. This is very important and really essential in connection with railroad operation because of the fact that abnormal and emergency conditions occur much more frequently in railroad operation than in probably any other industry, and it is impossible for the road to control or prevent the occurrence of such exceptional demands.

The most recent large power contract for railroad operation that the writer has knowledge of was negotiated and consummated last year between the Pennsylvania Railroad Company and the Philadelphia Electric Company at Philadelphia. This is a continuation and enlargement of an earlier contract covering the supply for the Pennsylvania Railroad's suburban service in Philadelphia, intended to provide for all traction requirements in that territory including through electrification between New York and Washington and elsewhere, if and when carried out, for a period of 20 years.

The power company contracts to supply the power at 25 cycles single-phase 13,200 volts at certain main supply points in the vicinity of Philadelphia or elsewhere as may be arranged from time to time. The railroad steps up the voltage to 132,000 and transmits at this pressure to its various transformer stations along the railroad.

The outstanding new feature of this power agreement is that the charges or rates are based on the actual cost to the power company of producing power in its generating stations, and of transmitting it to and converting it at the supply points. This actual cost, of course, includes fixed charges, general expenses, and all other items properly entering into the total cost.

In order that the railroad may be protected against any unforeseen high cost of producing power, the power company guarantees that the demand charge and the energy charge shall not exceed certain stipulated values that were estimated and set up at the time of the negotiations. Such guarantees are based on specific cost of coal and labor. Maximum rates for fixed charges are also stipulated.

Some of the other main features of the contract are:

Demand determined monthly based on three maximum normal clock hours per month.

Abnormal demands resulting from accidents, derangement of power supply, abnormally heavy traffic, or severe weather conditions, shall be disregarded in determining the maximum demand.

Demand may not be less than 75 per cent of any previous maximum demand.

Guaranteed monthly load factor is 30 per cent.

Guaranteed power factor is 55 per cent.

If lower rates are subsequently made to other consumers under similar conditions of supply, the railroad shall be entitled to the same rates.

At an average monthly load factor of 62 per cent, a coal cost of $5.00 per net ton, present labor rates, and guaranteed maximum demand and energy costs, the average cost to the railroad at the supply point or points under this contract works out 0.75 cent per kw-hr.

Sidney Withington: The question of power supply for railroad electrification is one not only of economy, but of reliability. These two important considerations do not necessarily go hand in hand; in fact, it often happens that a balance or compromise between them is necessary. For instance, it may be more economical to develop a single central supply of power for a given electrification project than to provide several sources of feed, but a single supply may mean that power-transmission facilities must be installed along the railroad right-of-way in close proximity to the tracks, with consequent danger of interruption on account of derailments. The right-of-way, furthermore, often passes through thickly settled communities where the clearance is restricted and where danger of trouble from a possible fire on adjacent property is considerable. Any hazard which results in cutting the power line in two obviously is going to be serious if it results in a complete prostration of service beyond the break.

As an alternative to a single point of supply there may be considered a main or central feed to serve as a "back bone," with supply points of relatively less capacity near each end of the electrified zone, so arranged that in the event of a failure of the main supply or a break in the transmission facilities the auxiliary source, may carry at least a portion of the load and thus take care of the most important service until normal conditions are

resumed. Such an arrangement obviously costs somewhat more than a complete concentration, but the resulting increase in reliability is often worth the added cost in an important electrification project.

A third possibility which may sometimes be practicable is the tying at various points to a single large power system with a transmission network entirely independent of the right-of-way of the railroad. Such a system is often fed from two or more independent power plants or interconnected with other power systems. In an arrangement of this kind any single interruption of power or transmission would normally not seriously affect railroad operation. If conditions are favorable, such an arrangement is from many points of view quite ideal, for it allows advantage to be taken of the maximum railroad load factor with consequent minimum cost, and at the same time obviously produces maximum reliability. The choice of power supply in any given instance obviously depends upon local conditions and facilities readily available.

Although in many instances a generated frequency of 25 cycles is available commercially which makes possible a tie directly into railroad traction feeders, the power available from a large commercial system, is usually 60-cycle three-phase, and is thus often not adapted for direct supply without modification for heavy electric traction, and therefore, regardless of the system of electrification, some form of conversion apparatus is generally necessary if power is purchased. If a railroad produces its own power the characteristics of the power supply of course are correlated with those of the system adopted.

The two electrification systems of power distribution most often employed in this country are (2) direct-current, operated at various voltages from 600 to 3000, and (1) alternating-current single-phase usually operated at 25 cycles and 11,000 volts. To adapt three-phase 60-cycle power from a commercial 60-cycle supply to either of these systems requires some form of substation apparatus, which in the case of direct current may be mercury-arc rectifiers, motor generators, or rotary converters, and in the case of single-phase takes the form of motor-generator frequency changers.

Other things being equal, the purchase of power by a railroad for traction purposes should be more satisfactory than the operation by the railroad of its own plant. The capital requirements for railroad electrification are necessarily very high at best. The cost of power distribution facilities required to convey power to the collecting devices of the motive-power units runs into many thousands of dollars for each mile of track electrified. The acquiring of locomotives or cars on an equipment trust allows postponement to some extent of a portion of the immediate capital requirements, but the purchase of power will eliminate the relatively large capital which would be necessary for its own power-plant installation.

It is, however, necessary that power companies which are interested in supplying power for railroad electrification shall consider all the aspects of the questions, such as diversity of load compared with other customers (for much of the railroad load, especially freight, occurs during the night), and the volume of business involved.

With growing efficiency of power-plant apparatus made possible, especially by concentration in large units, it is logical to expect that the production of power by organizations specializing in such production would be more economical than production by railroads themselves, provided, however, that such economies are not obtained at the expense of too high investment charges, so that the consumer does not have the benefit. It should be borne in mind in this connection, also, that railroads are often in a position to purchase coal more advantageously than power companies.

Railroads do not as a rule pay as high a rate of interest on capital investment as do power companies, and this should be taken into account in determining the demand or primary charge which represents the cost of the money invested in plant and associated facilities. If a railroad installs its own plant, it may justly contemplate calling upon its reserve capacity for such emergencies as may sometimes occur in the course of its operation; and a power company in taking on a railroad power supply should be prepared to carry the load, during abnormal conditions over which the railroad often has no control, without subjecting the railroad to penalty in establishing demands. As has been pointed out by Messrs. Schuchardt and Hill, most of the important agreements for power for railroad traction purposes now recognize this important point, to the mutual advantage of all concerned.

The early New Haven electrification, inaugurated in 1906, was originally supplied from a railroad-owned power plant located at Cos Cob, Conn., which is not far from the center of the system load between New York and New Haven. Commercial power at that time was not available. The Cos Cob Plant, with a capacity of about 13,000 kw., served the initial installation between New York and Stamford. In 1912 the plant was enlarged to about 32,000 kw. capacity to carry the New York, Westchester & Boston and the Harlem River Branch freight traffic and the electrification through to New Haven which was inauguarated in 1914.

In 1915 there was added to the power system a supply from the United Electric Light & Power Company at West Farms, N. Y., the power being generated at the Sherman Creek Power Plant of that company. This connection is supplied from turbo generators used exclusively for railroad service, and although the power company's machines share with Cos Cob the power swings, nevertheless with proper supervision considerable accuracy in the control of load and consequent supply of energy is possible.

With the growing load on the New Haven the question of a power supply at the east end of the electric zone was considered. The alternatives were (1) concentration at Cos Cob with independent high-voltage transmission and step-down substation at the east end of the zone, and (2) entirely independent supply at the east end, somewhat analogous to the West Farms supply. The result was a decision in favor of independent supply and the installation at Devon, Conn., of two 5000-kw. (continuous) frequency-changers for the purchase of power from the Connecticut Light & Power Company, and at New Haven of one machine of similar capacity for interchange in either direction of surplus power with the Connecticut Company.[1] These facilities automatically allow continuous or definite control of load as desired, regardless of relative variations of voltage, load, or frequency in any of the systems involved.

An extension of the New Haven System over the New York Connecting Railroad and on the Long Island Railroad to Bay Ridge, N. Y., made desirable a connection with the Pennsylvania Railroad power system at East New York which could be used in emergency. A motor generator similar to that at New Haven was thus installed at that point. That motor generator, as well as all of the other apparatus of that type, is available as a synchronous condenser to maintain a favorable power factor. There are thus now in service on the New Haven System five points of supply: East New York, West Farms, Cos Cob, Devon, and New Haven.

There is no doubt that the concentration of power at Cos Cob would have been more economical than the policy of decentralization which has been adopted, but the consideration of reliability justifies the extra expense. While Cos Cob is the main source of supply, the auxiliary sources are of sufficient capacity in the event of an emergency to provide the continuance of at least the more important traffic, and it is our opinion that there is a satisfactory balance between the two important considerations, economy and reliability.

1. *Interconnection of Power and Railway Traction Systems by Means of Frequency Changers*, by L. Encke, see p. 1056.

G. I. Wright: I want to make a few remarks about the economic aspects of such a service as the electrified Illinois Central, and these in general will apply to any suburban or commuter service for passenger traffic for a large city.

The handling of such a business is not particularly attractive from an economic standpoint, but although passenger revenues and passenger business for the railroads as a whole are falling off, yet suburban business is either holding its own or in most cases increasing.

The paper states that the load from the power company's standpoint is a favorable one, and I presume it means economically favorable. Suburban passenger business from a railroad standpoint is in general not economically favorable, and one of the most interesting things in connection with the electrification of such a service is its effect upon the net return. This business is a low-load-factor business; actually the ratio of the average number of passengers hauled to the maximum number hauled during rush hours is around 25 or 30 per cent. This means that the rolling stock and the total investment in railroad facilities necessary to handle the business is largely idle during the greater portion of the day.

A power company in selling electricity gets a return on a low-load-factor business by having a rate which takes into account the maximum demand. I believe the fact that their rates bring them a return for the service rendered and the investment necessary to handle that service is largely responsible for the growth and success of the power companies in this country.

With a railroad handling commuters this is not so. The rate for passengers who ride during the rush hour is very much lower than the rate for a ticket to ride during any part of the day. The latter have to pay 3.6 cents a mile. The rate for the commuter, in the case of the Illinois Central, is as low as 0.6 cent a mile. This means that for this low-load-factor business they are getting a very low unit price.

I do not believe that power people who are accustomed to their unit rates varying with the load factor of the load realize what the railroads are up against from the standpoint of economically getting a return on the service rendered. The railroads have probably not done as much to correct this condition as the power companies have. The power companies have insisted on a rate which takes into account the load factor. They have also given off-peak rates and have constructively gone at the problem of building up their load factor and increasing the off-peak business. The railroads under steam operating conditions have done very little. After electrification it is possible to make improvements in this respect. You can operate economically shorter trains and more frequent train service during the middle of the day and thus make a bid for that business as has been done by the Illinois Central. The cost of fuel for steam operation is the same no matter what time of day it is burned in the locomotive, while the cost to the railroad of electric current used during the non-rush hours is only a fraction of the cost if used during the rush hours, as it does not increase the power company's investment or the demand charge which brings them the return for this investment.

The Illinois Central's electrified service with its faster schedules and greatly increased frequency of train service in the non-rush hours, has not only attracted new residents to the territory served but has increased the riding habit of those already there. The Sunday business has also been greatly increased by this method. The Illinois Central has also put into effect a reduced round-trip rate of a fare and a half and has made a bid for the business of those who would hesitate to pay 3.6 cents a mile to make a trip down town. I believe they could well afford to have made this rate still lower.

It must be highly gratifying to the management that they have been able to turn a large operating loss into an operating profit sufficient to pay some return on the increased investment, and this with lower rates than are charged for most similar services. This fact should also be of interest to the management of other railroads who have not as yet electrified their suburban services.

H. C. Sutton: Most electrifications in the East have been for suburban service. A factor that is very interesting to the central stations is that with the extension of the electrifications to take in trunk-line railroads, the load factor of 26 to 30 per cent which is now obtained on suburban service, will be increased to a load factor of over 60 per cent with combined suburban and trunk-line electrification.

A study is being made of the electrification of an important railroad in the East where the peak load occurs in the early morning hours, due to the schedule of getting the trains into the metropolitan terminal early in the morning. This should result in a high diversity factor for the central station for this type of load.

There are some reasons why purchase of central-station power should prove of benefit to the railway, which have not been brought out in the papers. Take, for instance, the cost of supplying service by the central station as compared with the cost of the railway company's putting in its own generating station. If the railway furnishes its own supply it would have to build a plant at considerable expense, namely, a modern plant of the day in which it is designed and built. However, past history would indicate that in a ten-year period that plant would be relatively uneconomical as compared with plants built at later dates. Under central-station supply additions to the generating capacity are continually made to take care of the rapidly growing load, where in many locations the load doubles in five- or six-year periods. Central stations, therefore, are continually building new and better plants with an advance in higher efficiency, with the use of larger turbine units, etc., bringing down the cost of power from year to year. The railway company, therefore, should benefit in future readjustment in rates when based on the cost of supply.

There is another interesting fact in regard to suburban railway electrification and that is the rate of the growth of traffic is greater than prior to the electrification due to the greater ease and comfort in riding on the electric trains.

O. K. Marti: I was very much interested in the paper by Messrs. Schuchardt and Vandersluis, especially since mention is made in it of the new converting equipment used, the mercury arc rectifier. This is the first main-line electrification with such devices in this country. Further, because of its peculiar operating conditions, this line imposes very high duties on the converting equipment, and it was therefore very interesting to learn more about the operation of the rectifiers.

As we all know, rectifiers have a very high efficiency at high voltages. The efficiency at 1500 volts is much higher than that of any other converting device. Since rectifiers for 2400 and even 3000 volts are just as satisfactory in operation, it would be interesting to learn whether Mr. Schuchardt could give any information as to the possibility of operating such a railroad as the Illinois Central at these higher voltages.

Another thing which I should like to bring out, and on which I should like to hear some comments, especially from railroad engineers, is whether a higher voltage drop on the trolley wires would not be permissible, and whether this would not be more economical from many points of view. Thus far compounding windings have always been used on old converting equipment, and other means as well have been employed to keep the voltage as constant as possible.

During the discussion of this paper Mr. Wright mentioned that a high load factor allows a smaller unit to be used for converting alternating to direct current, and is therefore very desirable. It seems to me that by allowing a high voltage drop in the machine we would get a still better utilization of the units, especially if the converting devices are distributed along the system instead of being concentrated in one place.

This directly relates to the question of the location and spacing of substations, namely, should rectifiers be grouped in substations

of comparatively large capacity or would it be more economical and advisable to locate them along the railroad line, distributed in smaller stations. An extensive railroad system which is at present being electrified is the Berlin Rapid Transit, which consists in part of a belt line uniting all the suburbs of Berlin. In this system the rectifiers are spaced very closely, and are located in the existing structure, in this case in the arches of the elevated structure supporting the tracks of the railroad.

P. H. Hatch: Electrification has been so far tied up intimately with power supply. In the future, it seems to me, we should consider the effect of independently propelled locomotives similar to, and having the advantages of, the electric locomotive but without the complications of the distribution system. I refer to the Diesel electric locomotive or the straight Diesel unit. It promises the combined advantages of the electric equipment. In the future what effect will this have on our power requirements?

Another problem is the question of standardization of frequency for railroad power supply. Those of us who are using the 25-cycle single-phase system are wondering if 60 cycles becomes standard what we will do for power conversion. Will we have to supply rotating machinery for converting our power? If such is the case, then some of the advantages of a-c. electrification in this country may not be entirely realized.

R. F. Schuchardt: The question Mr. Marti has asked me should have been asked of Mr. Vandersluis since it involves the railroad's choice of electrical system. Mr. Vandersluis will probably, however, agree with me that to go into this question at all would be to open up the entire subject of systems for railroad electrification, which is quite beyond the purpose of this meeting. However, it might be worth while to point out to Mr. Marti that among the deciding factors in the selection of trolley voltage, the efficiency of the substation equipment is not a paramount one.

W. M. Vandersluis: Our paper was prepared especially to bring to the attention of the power companies the necessity of studying the power needs of steam railroads contemplating electrification and meeting those needs squarely in offering their services. That the railroad requirements are different has been clearly brought out in the paper and in the discussion.

The agreement in question, covering service to an electrified steam railroad at seven different points and with all the required feeders to the right-of-way line, is the first of its kind. Naturally, it was entered into by the railroad company with some misgivings at times as to how it would work out. The length of the agreement so indicates, although it would have been much simpler if left entirely to the engineers of the two organizations.

It has been in operation for over two years and so far nothing has come up to indicate the necessity of any particular change in its various clauses. This is due not so much to the wording of the agreement as to the spirit of cooperation evidenced, we believe, by both parties in their desire to understand and meet the service requirements of each.

Power companies contemplating similar services to electrified steam railroads can profit by the attitude of the companies in question and the results obtained.

Effect of Street Railway Mercury Arc Rectifiers On Communication Circuits

BY CHARLES J. DALY[1]

Associate, A. I. E. E.

Synopsis.—This paper describes the effects experienced on the telephone circuits from the two mercury arc rectifier substations recently installed in Bridgeport, Conn., and shows in table form the relative magnitude of the interfering effects between rotating equipment and mercury arc rectifiers as a means of energizing the street railway system. The method and the type of apparatus used to reduce the effects experienced from the rectifiers are also described.

* * * * *

THE application of the mercury arc rectifier for supplying power to street railway systems is now attracting a great deal of attention. In considering such an installation the question naturally arises as to its effect on communication circuits. In December 1927 all the current for the operation of the street railway system serving the territory in and around Bridgeport, Conn., was obtained for the first time from two mercury arc rectifier substations. A comparison of the relative interfering effects on the telephone circuits between this method and the previous method used for energizing this railway system was obtained and is described in this paper.

Both substations were not placed in operation at the same time, there being an interval of about four months between the installation of the larger station at Bridgeport and that of the smaller at Stratford. During this interval the larger rectifier station was operating in parallel with the rotating equipment of the old generating station for a short period of time only. Measurements of the interfering effect of the noise experienced on the various types of local telephone circuits were made just prior to the placing in service of the first rectifier station and immediately after each substation was connected on the line, as well as after temporary remedial measures were applied. The measurements obtained under these various conditions of energizing the railway system are shown in the accompanying tables.

TYPE OF TELEPHONE PLANT

The Bridgeport exchange is a multi-office area served by three sub-offices, two of which are in the same building located in the business center of the city within one-quarter of a mile of the larger rectifier substation. The third sub-office is located in Stratford, approximately four miles from the Bridgeport central office building and within a quarter of a mile of the smaller rectifier substation. The interoffice trunk circuits connecting the Stratford telephone office with the Bridgeport main telephone offices are in underground lead-covered paper-insulated cables and with the exception of about one-half mile are parallel to and in the same streets with the railway system. See Fig. 1.

All subscriber telephone circuits on the same streets with the railway circuits are in lead-covered cables or twisted pair wire. The greater portion of the cable plant is in underground construction, although there are several relatively long runs where the cables are on poles jointly occupied with street railway circuits, and in a few instances on the same poles with both positive and negative railway feeders. There are no open-wire telephone circuits on the same streets with the street railway circuits.

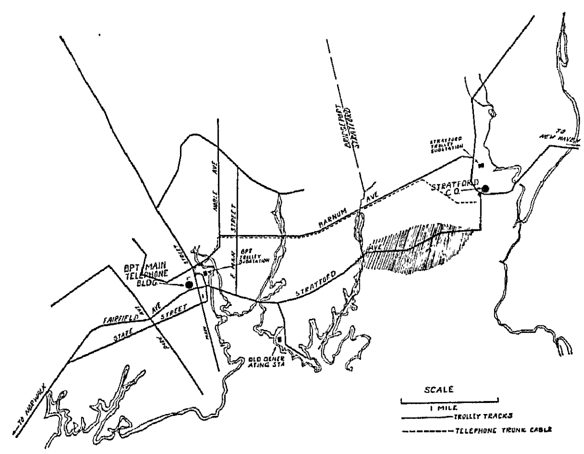

FIG. 1

The types of telephone service provided include standard individual line service on which metallic ringing is used, standard two-party selective and four-party semi-selective service, and private-branch-exchange service. In the selective service both the two-party and the four-party semi-selective types are provided.

It might be well to describe in some detail the signaling circuit used with the selective type of service. Fig. 2 shows the schematic wiring for a two-party selective circuit. It can be seen that each side of the telephone circuit is connected through a condenser, usually of 1 μ f. capacity, and then a ringer to ground. The ringer has a d-c. resistance of at least 1000 ohms and an impedance at 800 cycles of over 30,000 ohms.

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1. Transmission and Protection Engineer, Southern New England Telephone Co.

This connection to ground is used only for ringing purposes and not for transmitting the voice frequencies, as may be judged from the impedance in the ringing circuit to ground. With this arrangement the bell at one station can be rung independently of the one on the other side of the circuit.

The four-party semi-selective service is similar to the two-party service described above except that two stations are connected to each side of the circuit. With this arrangement, however, both bells on the same side of the line are rung when the ringing current is imposed on that particular side of the circuit. In the case of the individual-line service, signaling is obtained on an all-metallic basis by bridging the bell circuit across the telephone line.

Street Railway System

The street railway system consists for the most part of a double-track system with the rails and earth, supplemented along some of the routes with negative feeders, as the return circuit. Fig. 1 shows the railway system within the Bridgeport and Stratford city limits and the relative locations of the two rectifier substations. An interurban line extending to New

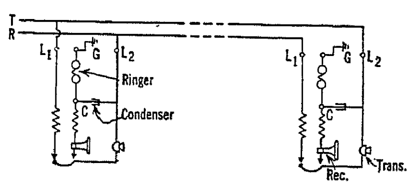

Fig. 2

Haven is furnished power from the Stratford substation for approximately half the distance or about seven miles. Another interurban line runs to Norwalk and is furnished power from the Bridgeport rectifier station for only about eight miles of its entire distance.

At the Bridgeport station there are five six-phase rectifiers which are energized from a 13,900-volt, three-phase, 60-cycle power line and deliver 600 volts direct current to the street railway system. Each rectifier is rated for 2000 amperes. Two similar type rectifiers are in the Stratford substation operating under the same conditions and in parallel with the Bridgeport station.

At the time of the writing of this paper a temporary filter had been installed in the street railway circuit in the Stratford rectifier station, but none had been installed at the Bridgeport rectifier station, although permanent filters were in the process of manufacture for both stations.

Method of Making Measurements

In order to determine the interfering effect experienced by the telephone subscriber under normal operating conditions, all measurements were made from the receiver terminals of the telephone instrument with the circuit connected through the switchboard to another telephone set located in the central office building. Measurements were obtained for various conditions that would be found in the practical operation of the telephone system. Such a condition, for example, is where two stations, due to the cancellation of the service or to the moving of the subscribers, have to be disconnected from a standard four-party semi-selective circuit leaving two stations connected to the same side of the circuit. This gives the maximum unbalance produced in this type of apparatus under the various operating conditions.

Results of Measurements

Prior to the cutting into service of the Bridgeport rectifier station, measurements of the noise on telephone circuits under various conditions were made at some 140 locations in Bridgeport and 50 locations in Stratford. After the installation of the rectifiers, measurements were made only at representative locations.

In Table I is shown the magnitude of noise obtained before and after the Bridgeport rectifier was cut into service in parallel with the rotating machinery in the old generating station. These measurements are representative of the general noise situation on the local telephone circuits.

TABLE I
NOISE UNITS

Location	*R*-(*T* & *R*)		*R*-(*T*)		*R*-bridged		2-*R* (*T*)	
Bridgeport	1	2	1	2	1	2	1	2
A	20	50	35	75	20	50	35	100
B	10	20	20	35	0	10	20	50
C	20	35	20	50	20	35	35	150
D	35	100	50	125	35	75	75	250
E	20	50	20	75	20	35	35	100
F	20	50	35	75	20	50	50	150
Ave.	20	50	30	70	20	40	40	135
Stratford	1	2	1	2	1	2	1	2
A	20	35	75	100	20	35	75	200
B	20	35	35	50	20	20	35	100
C	20	20	35	35	20	20	35	35
Ave.	20	30	50	60	20	25	50	110

R-(*T* & *R*) = Ringer and condenser connected from each side of circuit to ground.
R-(*T*) = Ringer and condenser connected from one side of circuit to ground.
R-Bridged = Ringer bridged across circuit, no ground connection.
2-*R* (*T*) = 2 Ringers with their associated condensers connected from one side of circuit to ground.
(1) = Before rectifier was cut in.
(2) = After rectifier was cut in.

The measurements on the private-branch-exchange trunk circuits also showed an increase in the order of 125 per cent, but with the exception of three cases this increase was not sufficient to impair the telephone service seriously. In these three cases it was found practicable to take care of the noise by rearrangements in the telephone plant.

On the day the Bridgeport rectifier was cut into

service, complaints were received from a number of telephone subscribers on account of the noise. The private-branch-exchange subscribers were the first to report the interference which in most cases was due to the large increase in the noise obtaining before the central office operator answered. This noise was greatly reduced, however, after the connection was completed. In order to reduce the noise level on some of the other circuits it was necessary to clear up some slight unbalances in the telephone plant which would not have had an appreciable effect with the rotating generating equipment furnishing the power.

There were no appreciable effects noted on the Bridgeport-Stratford interoffice trunk circuits.

When the Stratford rectifier station was put into service there was no appreciable effect noticed on the telephone circuits in Bridgeport except for a small area near the exchange boundary along Stratford Avenue, but in Stratford, especially along Stratford Avenue between the two rectifier stations as shown in the shaded area on Fig. 1, the noise effects were greatly increased and the reactions from the telephone subscribers more serious. The Bridgeport-Stratford interoffice trunk circuits, however, showed no appreciable effects.

After this installation three times as many complaints were received from telephone subscribers as were received when the Bridgeport station was installed. Most of these complaints were from party-line subscribers.

Table II gives a general idea of the noise conditions before and after the Stratford rectifier was installed as well as the results obtained after installing a filter in the railway circuit.

TABLE II

Location Stratford	*R*-(*T* & *R*)			*R*-(*T*)			*R*-Bridged			2-*R* (*T*)		
	1	2	3	1	2	3	1	2	3	1	2	3
A	20	325	150	75	500	300	20	300	125	75	800	450
B	20	100	65	35	200	85	20	100	65	35	275	125
C	20	35	35	35	75	35	20	35	35	20	110	50
D	20	100	75	35	200	100	20	85	75	35	350	200
Ave.	20	140	80	45	245	130	20	130	75	40	385	205

(1) Power from old generating station.
(2) Mercury arc rectifiers at Bridgeport and Stratford.
(3) Same as (2) but with rectifier and filter at Stratford.

Wave Analysis

A wave analysis of the noise experienced showed 360,- 720,- and 1080-cycle components with the 360 cycle the most prominent. This latter is the fundamental frequency, in this instance, of the ripple in the rectified d-c. voltage wave and is equal to the product of the fundamental frequency of the supply line (60 cycles) and the number of secondary phases of the rectifier (6 phases).

The amount of these harmonic currents flowing over the railway distribution system is a function of the harmonic e. m. f. generated and the load characteristic of the system. Under these conditions, the most practicable means of limiting the flow of these disturbing harmonics on the railway system, and by so doing limiting their interfering effect on the telephone circuits, was to install a filter on the load side of the rectifier. This means of reducing the disturbing harmonics has been used to advantage in other places where the railway current is obtained from mercury arc rectifiers.

Filter Equipment

The first filter equipment installed in the Stratford substation was only temporary, but similar electrically to the proposed permanent equipment which was in the process of manufacture for both substations.

The equipment consists of a 0.7 millihenry series reactor inserted in the negative return circuit at the station. This reactor acts as a choke to the harmonic currents and of course must be able to carry the entire load current furnished by the station. There are also three resonant shunts connected between the positive and negative sides of the railway circuit on the load side of the reactor in order to by-pass harmonic current at 360, 720, and 1080 cycles, thereby reducing the voltages applied to the line at these frequencies. Each of these resonant shunts has a 2 millihenry air-core coil

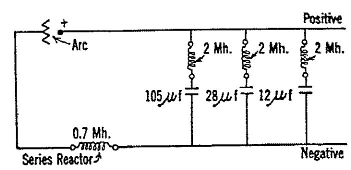

Fig. 3

in series with a bank of condensers. Tuning is accomplished at each frequency by varying the capacity until the harmonic line voltage is a minimum. The capacities obtained for resonance were 105, 28, and 12 μ f., respectively. The condenser banks are built up of 1 μ f. units made to withstand 600 volts direct current indefinitely. See Fig. 3.

Results of Filter Installation

The effect of the filter on the noise levels in the telephone circuits in the Stratford exchange area was quite appreciable and the complaints from the telephone subscribers dropped to only a few cases in the shaded area along Stratford Avenue. The noise measurements obtained are shown in column 3 of Table II. Measurements made with the temporary filter installed in Stratford indicated that a large part of the remaining noise, given under column 3, resulted from the unfiltered rectifier at Bridgeport. It is expected that when a filter is also installed in the Bridgeport substation a further reduction in the noise levels in this particular area will be obtained.

Conclusion

The magnitude of the interference from a given source, in this case the mercury arc rectifier, depends

on the distribution and type of plant of both the street railway system and the telephone system. As shown in Tables I and II, this is clearly indicated by the more serious reactions obtained on the same types of telephone circuits in the Stratford area than in the Bridgeport area. The type of rectifier installed in both areas is the same, but in the Stratford area a larger percentage of the telephone plant is in aerial cable construction with more joint pole line construction with the railway circuits than in the Bridgeport area, where the degree of exposure between aerial telephone and street railway circuits is relatively small.

From the experience obtained with the installation of the six-phase mercury arc rectifiers for the street railway system in Bridgeport and adjacent territory, it can be definitely stated that in general a street railway system energized by mercury arc rectifiers possessing no means of limiting the harmonic components has a greater inductive influence on neighboring communication circuits than when energized by rotating equipment. General experience has shown, however, that by means of properly designed filtering apparatus installed on the d-c. load side of the rectifier, the inductive influence of such a rectifier may be reduced to a level comparable with that of rotating equipment of good wave shape.

Discussion

P. W. Blye: In connection with Mr. Daly's paper, it may be of interest to outline briefly interference conditions which have resulted from the operation of mercury arc rectifiers on street railway systems in other locations and to describe the work which has been done jointly by the telephone company and the electrical manufacturers in an effort to provide satisfactory measures for reducing these effects. In all cases of interference which have been investigated so far, the a-c. supply systems have been in underground cable or have not been involved in telephone exposures. The interference has therefore resulted from harmonics in the output side of the rectifier only.

As pointed out in Mr. Daly's paper, the ripple in the output voltage of a mercury arc rectifier consists of a fundamental component and its harmonics, the frequency of the fundamental being equal to the product of the frequency of the supply system and the number of secondary phases. In the case of a six-phase rectifier operating from a 60-cycle supply system, the principal alternating components in the output voltage and current, from the standpoint of inductive coordination, would therefore be a fundamental having a frequency of 360 cycles and its second and third harmonics having frequencies of 720 and 1080 cycles respectively. From measurements made on a number of 600-volt rectifiers in the field, the average magnitudes of these three components have been found to be as follows:

360 cycles.........32 volts
720 cycles......... 8 volts
1080 cycles .... 3.5 volts

The a-c. components impressed on the trolley and feeder system by a rectifier are, of course, a function of the above voltages and the impedance of the system. The impedances of the systems investigated so far have been found to be inductive reactances which tend to suppress the higher frequency current components. In a representative location in which severe inductive interference was experienced, the most important a-c. components in the trolley and feeder system were found to be as follows:

360.........17.5 amperes
720......... 2.0 amperes
1080......... 0.5 ampere

Experience so far has been chiefly with 6-phase rectifiers. A limited amount of experience with 12-phase rectifiers has indicated that while the inductive effects are less than with 6-phase devices there is an inductive coordination problem here also.

In single substation areas the individual stub-end feeders offer a relatively high impedance to the alternating currents generated by rectifiers. In the case of tie feeders connecting rectifier substations with other stations in which rectifiers or rotating equipment are in operation, however, this terminal apparatus provides a low impedance path for the alternating currents and relatively large currents may be expected in such feeders. A somewhat similar situation exists in the case of single substation areas where main feeder routes are involved. The most serious cases of interference may therefore be expected from tie feeders of this character.

Coordination between exposed telephone circuits and street railway trolley and feeder systems such as these which, of course, employ a ground return, is difficult owing to the fact that power system transpositions are impossible.

During the past year, interference has been experienced from a number of rectifier installations in this country and in Canada. While practically all types of telephone service have been affected, the most serious effects have been noted in the case of interoffice trunk circuits, party-line subscribers' circuits, and private-branch exchange systems.

The severity of the interference, of course, varies considerably with the separation of the power and telephone systems. The most severe effects have been noted on telephone circuits carried in aerial cables on the same poles with the trolley system feeders. Serious effects have, however, been noted in long exposures on similar aerial cables located several hundred feet from the trolley system. In a majority of cases the noise has been found to be due to electromagnetic effects resulting from a-c. components in the feeder system.

In one of the most severe cases of interference, noise was measured on party-line circuits in the affected area of the order of 1000 to 2000 units. On interoffice trunk circuits in this area, noise of from 1500 to 2000 units was observed. A number of P.B.X.'s was also seriously affected and while conditions in these cases were improved somewhat by measures taken in the telephone plant, it was not possible to reduce the noise to a satisfactory level by this means. Several other similar cases of severe interference have been experienced as well as a number of cases of a less acute nature such as those in Bridgeport and Stratford, covered in Mr. Daly's paper.

During the past year cooperative studies have been carried on by the manufacturers and the telephone company on methods of improving the wave-shape of rectifiers. This work has indicated that the most effective arrangement is a filter employing a series reactor and a number of shunt branches tuned to the frequencies of the various alternating components to be suppressed. In such a filter the series reactor must carry the full d-c. output of the rectifier. The shunt condensers must withstand the maximum voltage to be expected on the system. These condensers and the shunt coils must carry continuously alternating voltages generated in the rectifier divided by the reactance of the series reactor.

In one of the cases in which severe interference was experienced the filter arrangement used was the same as the temporary installation at Stratford described by Mr. Daly. This filter proved entirely satisfactory as a means of reducing the interference, the important alternating voltage and current components and, therefore, the induced noise, being reduced in ratios of the order of 10:1. Installations of a generally similar type have been made in other locations, and in each case the telephone

circuit noise has been reduced to a level comparable to that experienced with the rotating equipment formerly used.

The permanent filters for the Connecticut rectifiers have only recently been installed and complete measurements of their effectiveness have not yet been made. Preliminary measurements in the Stratford Area indicate, however, a reduction in the noise of approximately 8:1.

The results of the cooperative work so far have indicated that satisfactory coordination can be effected between telephone circuits and the d-c. street railway circuits when the latter are supplied either by rotating equipment or by rectifiers equipped with suitable filters.

R. G. McCurdy: Mr. Daly's paper on the effect of mercury arc rectifiers on communication circuits treats the matter of coordination between the street-railway feeders and trolley system, and local telephone circuits. He has shown that it is practicable to coordinate such street railway and telephone systems when mercury arc rectifiers are used as the converting equipment and provided suitable filters are employed with the rectifiers. The matter of the effect of the mercury arc rectifiers on coordination with a-c. supply lines has not been covered.

Inductive coordination difficulties so far experienced by the Bell Telephone Companies with power circuits employing mercury arc rectifiers have been confined to the d-c. side. The a-c. feeders to the mercury arc rectifiers have either been in cable or else in relatively short overhead feeders not involved in any extensive exposures with telephone circuits.

In connection with various tests which have been made on rectifier installations in cooperation with the manufacturers and operating companies, considerable data have been gathered on the effect of the rectifiers on the wave shape of the a-c. system from which it is supplied. This has indicated that the six-phase mercury arc rectifiers take an alternating current having a telephone interference factor, in the case of 60-cycle systems, of from 300 to 500. There are present all the odd non-triple harmonics, being the harmonics immediately below and immediately above the even harmonics appearing on the d-c. side. The experience with 12-phase rectifiers has been less extensive but it is expected that the harmonics and the telephone interference factor will be lower than with 6-phase rectifiers.

The wave-shape distortion introduced into the a-c. voltage wave will, of course, depend upon the impedance of the a-c. system from which the rectifier is supplied. In a large system with comparatively short feeders, the distortion in the voltage wave will be comparatively small. With comparatively long feeders or a system of small size, considerable voltage distortion may be experienced.

Where overhead lines supplying mercury arc rectifier loads are involved in exposures with open-wire telephone lines, the difficulties of inductive coordination will be greatly increased over that experienced with the usual type of load. The degree of difficulty will increase with the increase in voltage and current telephone interference factors caused by the use of the rectifier. This problem is much more likely to be met with in cases of interurban electrifications or electrifications of main line railroads involving a-c. transmission over considerable distances than in street railway installations where the a-c. feeders will more often be in cable.

J. W. Milnor: It may be of interest to mention the experience of the Western Union Telegraph Company in connection with interference from installations of mercury arc rectifiers.

These remarks will be confined solely to inductive interference with telephone-circuit operation. We have not yet found any serious interference with the types of telegraph circuit now generally employed in handling the company's business. Our general experience indicates that interference from the trolley (d-c.) side of a rectifier installation is severe to telephone circuits if filters are not employed. Such interference, however, is mitigated considerably by the employment of the type of filter which Mr. Daly described.

Mr. Daly has confined himelf to the discussion of interference from the trolley (d-c.) side, and it is here I think that one's impression might be somewhat misled, if some mention were not made here concerning the other effects. The telegraph company has been concerned with one case where its line is paralleled by both the a-c. and d-c. sides of a rectifier system. The 6th, 12th, and 18th harmonics were found to be reduced by the filters, but the interference remaining was found to be severe at harmonics of the frequency of 5, 7, 11, 13, 17, and 19 times the fundamental (60 cycles). You will note that these frequencies are one harmonic removed above and below the 6th, 12th, and 18th which are characteristic of rectifier operation from a 60-cycle source. I regret that our investigations have not proceeded far enough so that we can present a more detailed discussion of this odd-harmonic induction, possibly to be attributed to the a-c. side of the rectifier system.

Our experience indicates that it is most desirable that further investigation be made so that we may have a better understanding of the matter of proper inductive coordination for rectifier installations. It is to be hoped that manufacturing companies and utilities contemplating the use of rectifiers where communication circuit parallelisms are involved, will give considerable thought to this matter prior to making a choice as to the type of equipment to be used in providing direct current for propulsion circuits.

O. K. Marti: In regard to Mr. McCurdy's discussion I should like to mention that interference due to an a-c. line supplying rectifiers is probably to be feared only if the entire load consists of rectifiers. In case the a-c. supply line also furnished power to other apparatus, such as motors, lights, etc., the rectifier load will not produce a distortion of the alternating current to any considerable degree. Since in almost every case some other load is connected to the line supplying a rectifier, this problem does not seem to be so serious. Besides, in cities and larger towns all the supply lines are brought into the substations in cables, which again will eliminate the possibility of interference with communication circuits. Due to the fact that the rectifier load is always a three-phase balanced load, the third harmonic and its multiples are eliminated from the line current by the transformer connections used. There is no residual line current and therefore very little possibility of interference. Further, it might be possible to improve conditions, where interference does exist, by alternately connecting a rectifier in delta and another one in star on the primary side, as this method of connection might filter out some of the harmonics.

W. B. Hall: I should like to show an oscillogram, taken at the Congress St. Substation, of the actual waves whose effects the previous speakers have been analyzing.

At very light load, the direct voltage will consist of successive peaks of the six-phase sine waves, as each anode carries the load alone for one-sixth of a cycle. The variation in voltage is from 0.866 to 1.000 or 13.3 per cent.

With heavy load (as shown in the top curve of the oscillogram, Fig. 1), the reactance of the six-phase transformer causes the anode which is carrying the load to continue to supply current, and causes the incoming anode to pick up the current gradually, so there is a period of overlapping during which two anodes are sharing the load. During this period, the direct voltage is as much below the incoming anode's sine wave as it is above the outgoing anode's sine wave, since the outgoing anode is dropping its load at the same rate that the incoming anode is picking it up, and therefore $L \frac{d\,i}{d\,t}$ for one equals $L \frac{d\,i}{d\,t}$ for the other. Hence the direct voltage follows a line exactly halfway between the two sine waves, as shown in Fig. 2, until the current in the outgoing anode has entirely ceased, when the direct voltage suddenly jumps to the sine wave of the incoming anode. The variation here is more than the 13.3 per cent, the amount depending upon the length of the period of overlap which depends upon the load.

But this is the wave of voltage variation, which could cause interference only by capacity coupling. The effect of capacity coupling at 600 volts is negligible. Most of the interference is by inductive coupling with the direct *current*. This current goes mainly to series motors which are highly inductive and draw a current wave much smoother than the voltage wave (see feeder current in the oscillogram). These oscillograms are all taken without the d-c. filter in service.

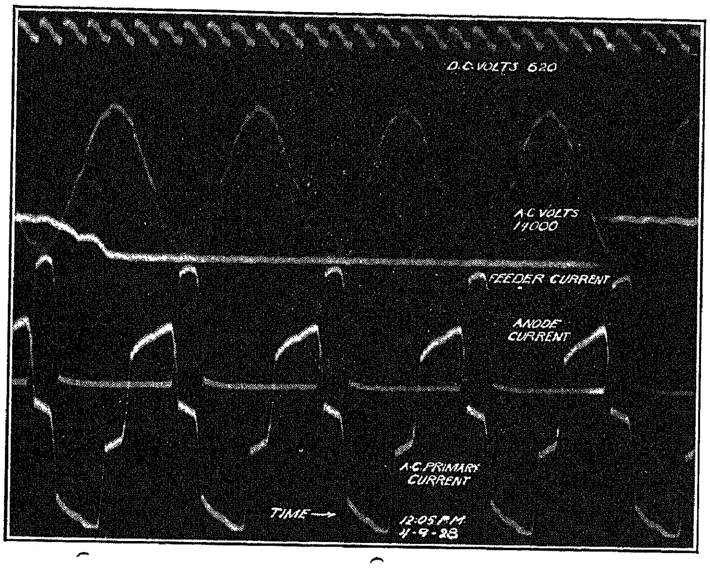

Fig. 1

This direct current is supplied successively by each anode in turn. Hence each anode supplies a direct current for 60 deg., then none. The anode current then is one rectangular block 60 deg. long for each cycle (see oscillogram).

The transformer primary current is the same as the anode current. But since the primaries are delta-connected, the line current has two successive anode current blocks in it. Hence the a-c. line current consists of a rectangular wave for 120 deg., then zero for 60 deg. and so on. The curve marked a-c. primary current shows this, superimposed upon the transformer exciting

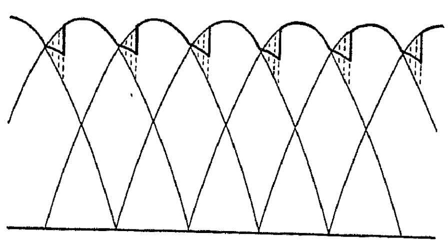

Fig. 2

current. These changes in line current are much more severe than the changes in the d-c. wave, and they are not remedied by inductance in the load or by d-c. filters. There would be much more inductive interference from the a-c. line than from the d-c. output, with equivalent exposure. Of course, the exposure of telephone lines to power lines is usually much less than to d-c. feeders and trolley wires.

The oscillogram (a-c. volts) shows the effect of this current wave on a-c. line voltage.

J. J. Smith: Mr. Daly points out in his conclusion that the interference from a given source depends on the distribution and type of plant of both the street-railway system and telephone system. The rectifier by nature of the mechanism through which it converts alternating current into direct current gives rise to harmonics in the d-c. voltage wave. If it were possible to obtain a rectifier which did not produce harmonics there would be no problem of telephone interference. On the other hand, even though harmonics are present in the power system, there would again be no problem of this type of telephone interference if the telephone lines were perfectly balanced. The real problem of interference is therefore to reduce the harmonics on the power system and the unbalances on the telephone system as far as is economically practicable.

On making a comparison in Table I under *R*-(*T* & *R*) 2 and 2-*R* (*T*) 1 it will be noted that the average noise units in each case are approximately the same although one set of measurements was made when the rectifiers were operating and the other set before the rectifiers were cut in. It will also be noted that with the rectifiers operating the average noise units in the telephone lines varied 3 to 1 due to the different degrees of balance in the telephone circuit.

While in theory any desired reduction in the 360-, 720-, and 1080-cycle components may be obtained by the use of reactors and resonant shunts, the addition of such equipment adds to the costs of the rectifier and the d-c. reactor introduces losses into the circuit, lowering the efficiency. It is, therefore, undesirable to make this apparatus any greater than is absolutely necessary.

Thus it would appear that the problem of interference from mercury arc rectifiers is a mutual one between the telephone engineers and the power engineers. The telephone engineers can reduce the noise considerably if they find means to take care of the unbalanced arrangement of selective ringers referred to in the paper, under 2-*R* (*T*) for instance, while the power engineers can assist in the reduction by the addition of filtering equipment.

It would be very interesting if Mr. Daly would amplify his paper slightly to give some idea of the exposures of the telephone lines to the trolley lines. I assume that the difference in noise units at different points is due to the different exposures of the telephone lines. In order to bring the data into a form in which they might be used for comparison with other rectifier installations, it would also be necessary to give the magnitude of the harmonics in both the voltage and current in the d-c. wave form of the rectifier.

In Fig. 3 in the paper the capacities and inductances given do not tune for the 6th, 12th, and 18th harmonics of 60 cycles. I find on checking up that the points at which they tune are 347, 675, and 1030 cycles. This is probably due to the fact that the coils are only approximately 2 millihenries. It might be well, however, to state this as it might lead to some confusion in the minds of persons reading the paper.

C. J. Daly: I feel that Mr. Marti is unduly optimistic as to the effect of reducing the harmonics by means of other loads connected to the a-c. line supplying a rectifier. It would be necessary that the impedance of such loads be small as compared to the impedance of the transmission line or feeder in order to produce any large reduction in the magnitude of the harmonic components transmitted over the line or feeder. It is also essential that the telephone exposure should not be located between the rectifier and these low-impedance loads.

In reference to the discussion by Mr. Hall, experience has shown that the induction from the d-c. side arises principally from the current harmonics. While these currents are small compared to the load current, as indicated by the oscillogram shown by Mr. Hall, the inductive effects are proportional to the magnitude of the harmonic components and not proportional to their values relative to the d-c. load current. As will be noted from the various values given in Mr. Blye's discussion, values of 360 cycles of the order of about 18 amperes have been noted when filters were not employed in the d-c. side.

I am somewhat uncertain as to the meaning of the term

"equivalent exposure" used in Mr. Hall's discussion. It is evident, however, that if the a-c. feeders consisted of one wire with rail return as in the case of the d-c. side, the interference from the a-c. side would be much more severe.

Mr. Smith's assumption that the difference in the noise values experienced on the telephone circuits was due to the difference in the degree of exposure is correct. For example, in the case of the telephone circuit to the *A* location on which 800 noise units were experienced, the exposure was much more severe than in the case of the telephone circuit to the *C* location where 110 noise units were obtained. The former circuit is in underground construction which parallels the railway tracks for about one-quarter mile and then extends in aerial cable for a distance of about one-half mile on the same pole line with both positive and negative railway feeders. The latter telephone circuit is approximately one-half mile in length, entirely in underground cable construction with an exposure of about one-quarter of a mile to the railway tracks.

In reference to the resonance points of the capacities and inductances, it may be pointed out that the coils are only approximately 2 millihenries and the capacitance values given are in terms of the nominal values of the condenser units. The actual capacitance may vary from these nominal values in the order of one per cent. As explained in the paper the branches were adjusted to be in resonance at the actual frequencies of the various harmonics to be reduced.

Rocky River Hydroelectric Development
Of The Connecticut Light and Power Company

BY E. J. AMBERG[1]

Associate, A. I. E. E.

Synopsis.—*This paper describes the Rocky River hydroelectric development of the Connecticut Light and Power Company, near New Milford, Connecticut, which is a storage development for regulating the Housatonic River below New Milford.*

There are no sites on the main river suitable for a large storage reservoir. It was therefore necessary to select a site on a tributary, the Rocky River. The run-off from the natural drainage area of the reservoir basin furnishes only a part of the water required to fill the reservoir, making it necessary to pump the balance from the Housatonic River against a maximum head of 240 ft. This is the first large application of pumped storage in the United States which accounts for the general interest shown in the Rocky River development.

The first part of the paper deals with the factors which have to be considered in determining the economic possibilities of such a development. The second part of the paper is a description of the main features of the development itself.

* * * * *

THE Rocky River hydroelectric development of the Connecticut Light and Power Company has created considerable interest among technical as well as non-technical men, as a project for regulating the flow of the Housatonic River below New Milford, Connecticut. Briefly, the development consists of a storage reservoir created on Rocky River, a tributary of the Housatonic, with a power and pumping plant on the Housatonic River; the power and pumping plant being connected by a single penstock with the reservoir.

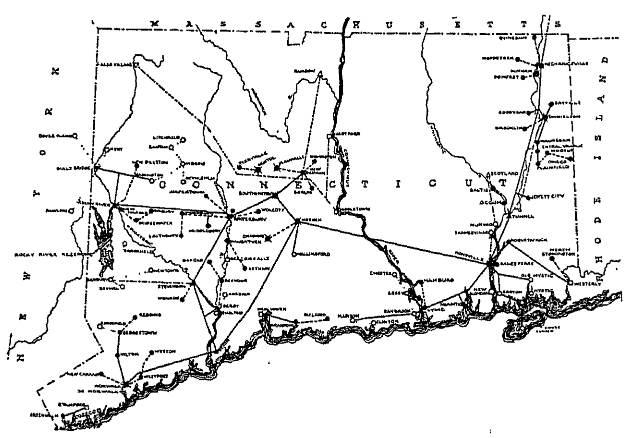

FIG. 1—MAP OF CONNECTICUT

Showing the system of the Connecticut Light and Power and Associated Companies, and their interconnections

■ Generating stations (steam)
□ Other companies' generating stations (steam)
▲ Generating stations (hydro)
△ Other companies' generating station (hydro)
● Communities supplied retail
○ Other companies supplied
⊗ Gas and electricity supplied
+ Gas supplied
——— Transmission lines
— — — Other companies' transmission lines
- - - - - Distribution lines
. . . . . . Other companies' distribution lines

Fig. 1 shows the location of the Rocky River development in relation to the system of the Connecticut Light and Power Company and its associated companies. Fig. 2 shows, on an enlarged scale, the vicinity of the Rocky River development. The Rocky River basin is located north of Danbury and west of the Housatonic River, and the site of the development is approximately 1½ mi. by state highway from the nearest railroad station at New Milford. The basin has a drainage area of approximately 40 sq. mi., eight and one-third of which are covered by the storage lake. The branches of the Rocky River heading near Danbury flow north to meet the branch of the river which heads near Sherman and flows in a southerly direction. From the junction of these branches, the river flows north through marshy flats which form the bottom of the reservoir, to a point 2½ mi. from the junction of the Rocky River with the Housatonic, wherein Rocky River falls about 200 ft. over a rocky bed. The shores of the reservoir are for the most part steep and rocky, rising to elevations of from 500 to 1000 ft. They are well covered with second growth timber together with some virgin timber in the more inaccessible locations.

The unusual features of this development lies in the fact that the drainage area of the reservoir basin will

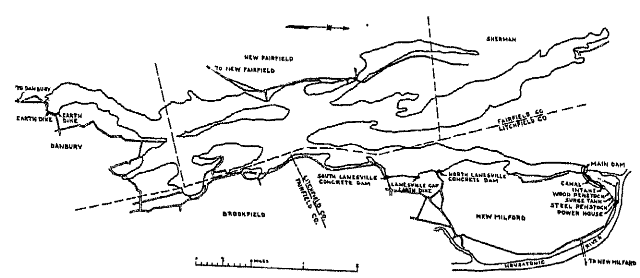

FIG. 2—OUTLINE MAP OF ROCKY RIVER RESERVOIR

supply only about 1.5 billion cu. ft. of water in an average year while the useful capacity of the reservoir is 5.9 billion cu. ft. All water above the natural run-off required to fill the reservoir must be pumped from the Housatonic River against a head varying from 200 to 230 ft. While considerable excess hydro energy will be available for pumping, the studies and investigations for this development are all based on using secondary steam energy for pumping, to be supplied from the

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Devon steam station of the Connecticut Light and Power Company.

The Rocky River reservoir may be likened to a large storage battery. Charging the battery is accomplished by secondary steam energy from Devon driving two 8100-hp. centrifugal pumps, delivering water to the reservoir. The battery is discharged by means of the 30,000-kv-a. generating unit delivering primary hydro energy.

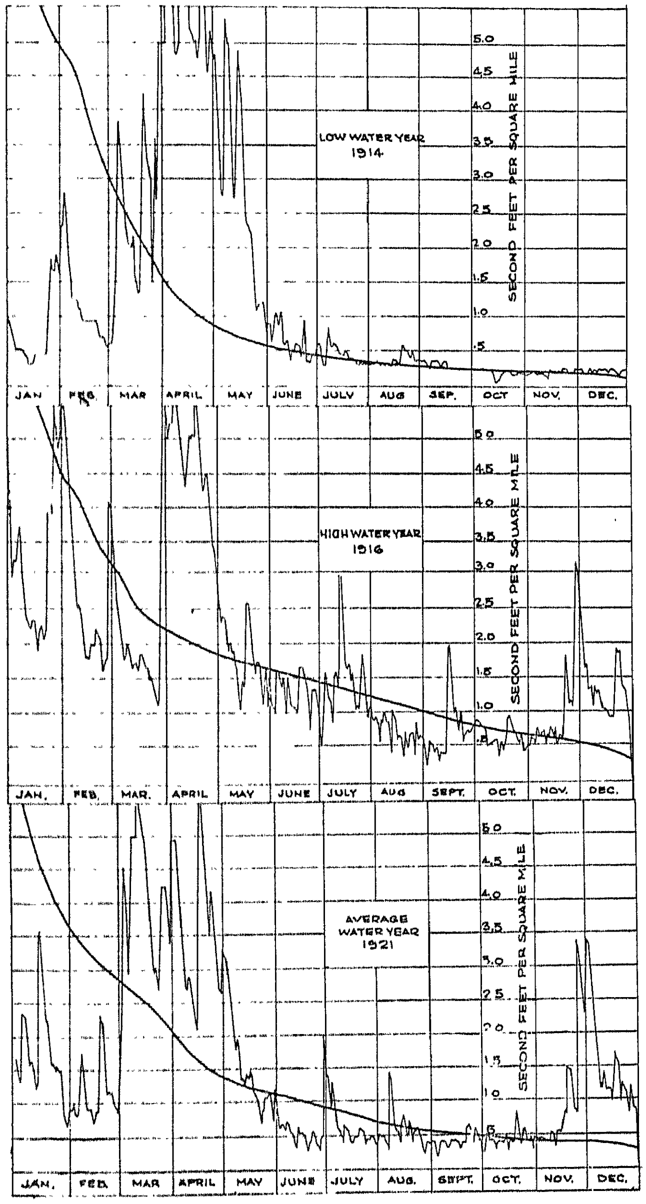


Fig. 3—Hydrographs of the Housatonic River

Showing hydrographs and superimposed flow duration curves for a low water year, a high water year, and an average water year

The efficiency of this storage battery for changing secondary steam energy into primary hydro energy is 61 per cent; this includes all losses from the 66,000-volt bus at the Devon Steam Station through the pumping units into the reservoir and back through the generating unit to the 66,000-volt Rocky River bus. In other words, for every 100 kw-hr. supplied by the Devon Steam Station in filling the reservoir, 61 kw-hr. are delivered by the Rocky River generating unit, when the water is drawn out again. We must not, however, overlook the fact that below the Rocky River plant there is an additional total average head of 191 ft. available, of which 71 ft. is efficiently developed at Stevenson. If the head at Stevenson is added, then for every 100 kw-hr. of steam energy, 79 kw-hr. of hydro energy are returned. If the total head from Rocky River to tide-water is added, 111 kw-hr. of hydro-energy could be obtained from every 100 kw-hr. of steam energy used in pumping.

Before going into a more detailed description of the Rocky River project, it is desirable to review, briefly, two factors which are essential to understand the basis upon which Rocky River has been developed. These two factors are: the hydrology of the Housatonic River, and the general character of the system load curves of the Connecticut Light and Power Company.

It is generally known that the rivers in the eastern

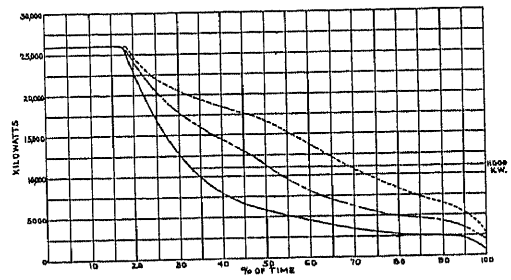


Fig. 4—Power Duration Curves for the Combined Output of Bulls Bridge and Stevenson Stations Without Regulation by Rocky River Development

Typical low water year 1914....................
Typical high water year 1916....................
Typical average water year 1921.................

	Drainage area	Net head in ft.	Kw. per cu. ft. per sec.	Installed capacity
Bulls Bridge........	782 sq. mi.	104	6.27	7,200 kw.
Stevenson..........	1510 sq. mi.	71	4.40	18,750 kw.
				26,000 kw. approx.
Rocky River........	35 sq. mi.	214.2 av.		
		Power—	15.55	
		Pumping	25.35	

Regulation by Rocky River development to produce 11,000 kw. firm 24-hr. capacity, expressed in kw-hr.

	Low water year	High water year	Av. water year
Rocky River output	31,100,000 kw-hr.	7,400,000 kw-hr.	17,400,000 kw-hr.
[1]Stevenson output	8,800,000 kw-hr.	2,100,000 kw-hr.	4,900,000 kw-hr.
Total output......	39,900,000 kw-hr.	9,500,000 kw-hr.	22,300,000 kw-hr.

1. Generated at Stevenson on water discharged from Rocky River

part of the country have a very irregular flow, unless some natural or artificial means exists for regulation. The Housatonic River, with which we are concerned, had no means of regulation; the stream flow shows very wide variations, as can be seen from Fig. 3, showing hydrographs and duration flow curves for a typical wet, average, and dry year. From the hydrographs, it is quite evident that the only period of the year when any reliance can be placed on the river flow is in the Spring-time. The rest of the year the flow is quite irregular. While frequently a somewhat larger flow may be ex-

pected in the Fall, there is no certainty of it, as shown for the dry year, where the low water condition continued right to the end of the year. With the river plants at Stevenson and Bulls Bridge operated in conjunction with the Rocky River storage plant the 24 hr. firm power of the hydro system is 11,000 kw. Fig. 4 shows the unregulated power duration curves for a typical dry, wet, and average year, limited by the installed capacities of the Stevenson and Bulls Bridge stations which together total 26,000 kw. The regulated 24 hr. firm power of 11,000 kw. obtained by the addition of Rocky River is also shown. The respective

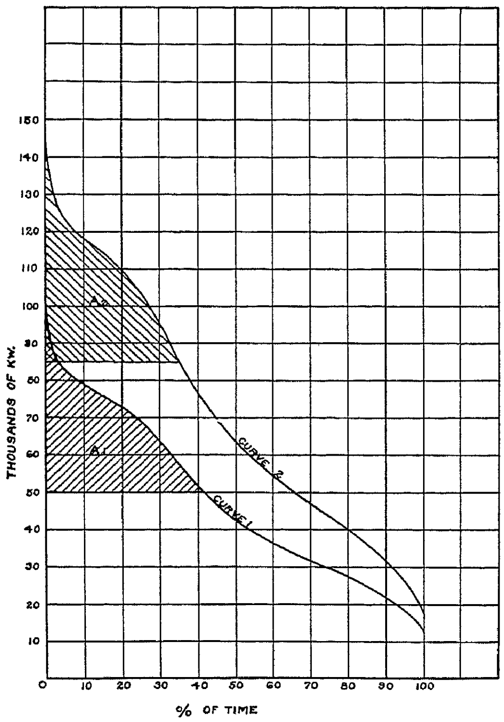


FIG. 5—LOAD DURATION CURVES

	Curve No. 1	Curve No. 2
Max. kw-hr	100,000	150,000
Load factor	47.3%	47.3%
Hydro kw	50,000	65,000
Increase		15,000
Hydro load factor	17.2%	13.2%

Hydro area A_1 = hydro area A_2

areas between the 11,000 kw. regulated firm power and the power duration curves represent the energy which has to be furnished from storage. The amount required in each year varies considerably, being 9,500,000 kw-hr. in the wet year and 39,900,000 kw-hr. in the dry year. Of these amounts, 78 per cent is produced by the Rocky River station and the balance at Stevenson, generated from the water released from Rocky River station.

By applying the 24-hr. firm power of 11,000 kw. to the upper half of the load curve, as shown in Fig. 5, curve 1, the total installed hydro capacity of 50,000 kw. can be used as firm capacity. Before regulation by Rocky River, the combined firm capacity of the Stevenson and Bulls Bridge stations was only 10,000 kw. although the installed capacity was 26,000 kw. Therefore, by installing a 24,000-kw. generating unit in the Rocky River station and by regulating the river the firm hydro capacity has been increased by 40,000 kw.

To obtain maximum benefit from such a storage development, it is necessary to apply it to that part of the load requiring the smallest number of kilowatt hours. This brings us to the second factor, the load curves.

When plotting system loads in the form of an annual duration load curve we will find that there is a decided peak. The reasons for this pronounced peak on the duration load curves, vary; in metropolitan districts the short-time lighting peaks are largely responsible; on systems like the Connecticut Light and Power Company where there are no short time peaks, of any extent, the seasonable changes in load are responsible. In the latter case, what appears as a very short-time peak on the duration load curve is the result of the 9-hr. day loads of the maximum days.

It can readily be seen that a different method of applying the hydro power is necessary in the two cases of peak load. In the first case of the metropolitan area, a weekly, possibly even daily, storage capacity will take care of the individual peaks, permitting the utilization of the river for actual demand without any seasonal storage. On the other hand, to take care of peak conditions on a system like that of the Connecticut Light and Power Company, seasonal storage in addition to weekly pondage is required. This seasonal storage is being provided in our case by the construction of the Rocky River storage reservoir.

Fig. 5 shows two annual duration load curves; curve 1 represents the present approximate combined load of the Connecticut Light and Power Company and associated companies, while curve 2 shows the expected combined load for the year 1931. The upper half of load curve 1 and load curve 2 for that matter, contains only 18.2 per cent of the total kw-hr.; the load factor of this part of the load is 17.2 per cent. The advantage of applying the hydro generating capacity to the peak of the load and the steam generating capacity to the base of the load is quite evident from a study of this load curve. Assuming that the total load has increased 50 per cent as indicated by curve 2 on Fig. 5, the same number of hydro kw-hr. represented by area A 2 would permit a firm hydro capacity of 65,000 kw. as against 50,000 kw. firm capacity of curve 1; or 15,000 kw. firm capacity could be installed without increasing the storage facilities. Additional capacity can often be installed at a low cost per kilowatt in existing plants, thus lowering the average unit cost per kilowatt of hydro capacity.

Such a storage development as Rocky River has therefore some inherent values which can be increasingly realized as the load increases.

Aside from the features discussed above, hydro plants have another great advantage in that they provide

standby capacity which can be made available in a fraction of the time required at a steam station, because to get up steam and warm up a turbine requires time unless boilers are kept in service and excess turbine capacity is kept on the line to take care of sudden load demands.

With the means of regulating the stream flow below Rocky River, it will be possible to develop the full head on this section of the river, which will then produce a total 24 hr. firm power of approximately 23,000 kw.

The hydro capacity will again be applied to the upper half of the load curve, which from curve 1 on Fig. 5 shows a load factor of 17.2 per cent. In order to take care of possible changes in the load curve we will make an arbitrary increase in the load factor of one-third, which will change this load factor to 23 per cent. With a 23 per cent load factor and a 24 hr. firm power of 23,000 kw. it will be possible to increase the total installed hydro capacity to 100,000 kw. by developing the full head of the river between tide-water and Rocky River.

The second 24,000-kw. unit at Rocky River is in addition to the 100,000-kw. capacity above referred to; its main function will be to act as a spare unit, which can be made instantly available. The second unit can be installed at a low unit cost including the raising of the reservoir level which will add approximately one billion cubic feet to the useful storage capacity.

From the above can be seen that the Rocky River development has a considerable increased future value, by making it possible to develop the full head below Rocky River as the load of the system of the Connecticut Light and Power Company and associated companies increases. Without Rocky River further economic development of the river would have been impossible.

In concluding the first part of this paper an account of water utilization at Rocky River and Stevenson stations for a typical average year seems in order.

As stated before with a full reservoir the water level will be at elevation 430 ft. The normal allowable draw-down is 30 ft., or to water level elevation at 400 ft. In this 30 ft. of draw-down, 5.9 billion cubic feet of water are taken from the reservoir. This amount of water, in going through the Rocky River generator will produce 24,200,000 kw-hr.

From the power duration curve for an average year in Fig. 4, it will be seen that 22,300,000 kw-hr. must be generated by water from Rocky River to maintain the 24 hr. firm power of 11,000 kw. Of the total of 22,300,000 kw-hr. the Rocky River station will furnish 17,400,000 kw-hr. while the remaining 4,900,000 kw-hr. are generated at the Stevenson station by the water discharged from Rocky River station. The amount of water that must be taken from the reservoir in order to produce 17,400,000 kw-hr. at Rocky River station is approximately 4030 billion cu. ft., based on an average figure of 15.55 kw. per sec. ft.

The water used for refilling the reservoir falls into two classes with two subdivisions in each class.

1. Run-off water from the Rocky River drainage area; this is subdivided into

a. Water held back at a time when it would have spilled over the Stevenson dam.

b. Water held back at a time when it could have been used at the Stevenson station.

2. Water taken from the Housatonic River and pumped into the reservoir, subdivided into

a. Water taken from the Housatonic River at a time when this water would have spilled over the dam at Stevenson.

b. Water taken from the river at a time when this water could have been used at the Stevenson station.

The following is a brief summary of the amount of water obtained from each subdivision for an average year.

1. The run-off from the Rocky River drainage area in an average year based on a net area of 35 sq. mi. is 1.6 billion cu. ft.

a. The daily discharge records for the average year show that there are 58 days of the year when the flow of the river equals or exceeds 2.86 cu. ft. per sec. per sq. mi., the flow necessary to produce 24 hr. full-load at Stevenson. The run-off during the 58 days amounts to 0.84 billion cu. ft. This amount of water, when finally released from the reservoir will utilize the additional head at Rocky River as well as at Stevenson.

b. The difference, or $1.6-0.84 = 0.76$ billion cu. ft., is Rocky River run-off that is caught in the reservoir at a time when the river flow was less than 2.86 cu. ft. per sec. per sq. mi. This amount of water, when finally released, will utilize the additional head of the Rocky River station only.

2. The total amount of water to be pumped in an average year is $4.03-1.6 = 2.43$ billion cu. ft. The possible number of pump hours per week with two pumping units available is 336 hr. Load conditions, however, will normally limit the actual pump hours per week to 200 hr. which corresponds to an average pumping rate of 298 cu. ft. per sec. as against the maximum possible rate of 500 cu. ft. per sec., which is the capacity of the two pumps.

a. The daily discharge records for the average year show that there are 58 days of the year when the flow of the river equals or exceeds 2.86 cu. ft. per sec. per sq. mi., the flow necessary to produce 24 hr. full-load at Stevenson, and 45 days when the river flow equals or exceeds 3.16 cu. ft. per sec. per sq. mi., the flow necessary to produce 24 hr. full-load at Stevenson after an average of 298 cu. ft. of water per sec. has been taken from the river at the Rocky River station. The amount of water pumped during this period is 1.32 billion cu. ft. This water when released from the reservoir will utilize the additional head at the Rocky River and Stevenson stations.

b. To completely fill the reservoir, an additional amount of $2.430-1.325 = 1.105$ billion cu. ft. of water

must be pumped at a time when the river flow is less than 2.86 cu. ft. per sec. per sq. mi. This water when released from the reservoir will utilize the additional head of the Rocky River station only.

TABULATION SHOWING SUMMARY OF WATER USED FOR FILLING THE ROCKY RIVER RESERVOIR IN AN AVERAGE YEAR

Classification	Water	Amount of water billions of cu. ft.	Will use "additional" head of Rocky River station	Will use "additional" head of Stevenson station
1 (a)	Run-off exceeding full-load flow	0.840	Yes	Yes
1 (b)	Run-off below full-load flow	0.760	Yes	No
2 (a)	Pumped water exceeding full-load flow	1.325	Yes	Yes
2 (b)	Pumped water below full-load flow	1.105	Yes	No
	Total	4.030		

Description of the Rocky River Development

Reservoir and Dams. The storage reservoir or lake is about 10 mi. long and 1¾ mi. across at the widest part. It has a surface area of 8⅓ sq. mi. and a shore line of approximately 60 mi. The creation of a lake of this size made it necessary to abandon and relocate highways and homes. Approximately 31 mi. of highway were abandoned and 9¼ mi. of new and relocated highway were built. Six cemeteries were relocated. Outside of several summer colonies located around the four ponds included in the basin, only 35 families with permanent residences were affected by the construction of this reservoir, which is an unusually small number considering the area covered. The bottom of the reservoir was for the most part swampy ground, and 4500 acres were covered with woods.

The main dam is located across Rocky River at a point about one mi. above its junction with the Housatonic River. It is an earth filled dam with a core wall. The lower part of this core wall consists of a two ft. concrete section which extends on the average ten feet above and an average of five feet below the ground surface. On top of this concrete section was placed a six in. Wakefield core wall (timber) reaching up to elevation 435 ft. On the west end, the concrete core wall was located in solid rock. This rock, however, dropped off rapidly below the surface at the location of the old river bed; from this point the core wall continued in earth. Fig. 6 showing a cross-section and plan of the dam gives a better idea of its construction than a lengthy detail description.

To take care of Rocky River during the construction of this dam a concrete conduit approximately 4 by 5 ft. was located near the original river bed. A small auxiliary earth dam with wooden sheet piling was erected across the river bed near the entrance to this concrete conduit, to create a small pond from which water could be pumped for the sluicing operation. The intake to this concrete conduit was equipped with a heavy wooden gate hinged at the top, used for closing off the flow through the conduit after completion of the dam. The material for the dam was obtained from the canal excavation, and was placed in the dam by sluicing. The relative elevations were such that only a very small quantity could be sluiced directly. So practically all of the material was excavated with drag lines and placed into large piles. It was then sluiced from these piles down into the dam. However, after the dam had reached a certain height, the slope in the sluicing line became insufficient; this was partly due too, to the increased distance of the drag line from the dam. When this point was reached the material was sluiced to a pumping plant located at elevation 375 ft. Before being delivered to the pumps, the material was passed through a revolving screen which eliminated all stone over 6 in. in diameter.

On the dam itself, a gasoline driven drag line was utilized to throw up small dikes on each edge to hold

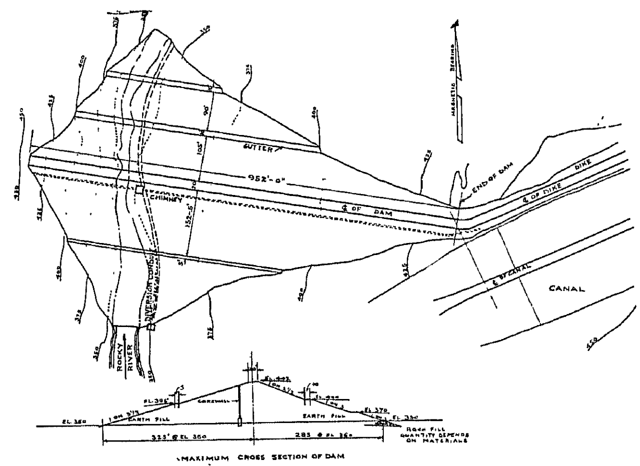


Fig. 6—Plan and Cross-Section of the Main Earth Dam

the water within the dam and give the sluiced material a chance to settle. Near the center of the dam was a concrete chimney with openings which acted as overflows for the sluicing water. The chimney connected at the bottom with the concrete conduit under the dam. As the dam came up the openings were closed up. The dike along the canal was constructed in a similar manner, as it constitutes practically an extension of the main dam.

To take care of some low points in the rim of the basin five smaller dams were necessary. Two of the dams are near Danbury. Both are earth dams of the same general design as the main dam. The material for these dams had to be hauled in as there was no water available for pumping the material from the borrow pits. It was wetted down and rolled. The other three dams are located near Lanesville. The north and south Lanesville dams are constructed of concrete. The so-called Lanesville Gap was closed by an earth dam similar in design to the main dam. Seamy rock

at the west end of this dam presented considerable difficulties in obtaining a tight job. The concrete section on which the 6 in. Wakefield core wall rested was considerably enlarged; in addition a considerable number of grout holes was put in the rock. The material was placed in this dam by sluicing.

The crest of the main dam and the Danbury dikes is at elevation 442 ft., or 12 ft. above the present normal maximum reservoir level at elevation 430 ft.

The crest of the dike at the Lanesville Gap is at elevation 440 ft. or 2 ft. lower than the crest of the main dam. This dike is located in a cove which practically eliminates all wave action, which accounts for the 2 ft. lower crest.

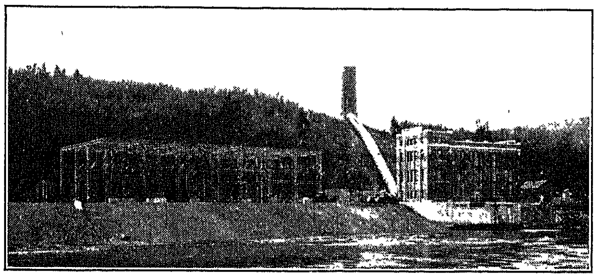


FIG. 6A—GENERAL VIEW OF POWER HOUSE PENSTOCK AND SUBSTATION

The present crest of the concrete section of the South Lanesville dam is at elevation 432 ft. and of the North Lanesville dam at elevation 431 ft. Each of these concrete dams is so designed that the concrete sections can later be raised four feet at a nominal cost. This construction would be done in order to raise the level in the reservoir from 430 ft. to 435 ft., which would add approximately one billion cubic feet to the reservoir. The future maximum water level in the reservoir is 440 ft., or an increase of 10 ft. over the present level. However, to raise the level to 440 ft. would require considerable additional construction work.

Intake. The canal leading from the reservoir to the intake was excavated for about 3300 ft. along the east bank of the valley. Terminating the dike in the side hill permitted the construction of a circular intake tower in the canal with only a short length of concrete conduit extending through the dike. Six equal intake openings are located in the half of the tower facing the canal. Each opening is protected by vertical trash racks provided with a compressed air rack raking device, and each opening can be closed by steel stop logs operated by means of manually operated hoists. A self-closing sliding Broome gate is located at the entrance to the concrete conduit in the tower and operated by electric hoist. Ample air-vents to the penstock are provided in the intake structure back of the gate. Necessary by-pass pipe connections are provided to fill the penstock from the intake with the Broome gate closed, and for filling the intake from the canal with the steel stop logs in position.

Penstock. The concrete conduit, having an inside diameter of 16 ft., extends only a short distance from the intake tower to the wood stave pipe line. This wood pipe line has an inside diameter of 15 ft. and extends for approximately 1007 ft. along the hillside. The average gradient is 0.5 ft. in 100 ft. The intake tower and wood pipe line are of sufficient capacity for the installation in the future of a second generating unit. The wood pipe line joins a steel penstock Y-connection; one of the two branches is blanked off ready for a second penstock for the future unit, while the other extends a short distance to a Johnson differential surge tank. Freezing of the water in this surge tank is prevented by agitation with compressed air. The compressed air pipe line follows the penstock from the power house, branching off at the surge tank, and on up to the intake for the air raking device, as previously mentioned. From the surge tank the penstock drops down the hillside to the power house (Fig. 6A). The inside diameter varies from 13 ft. to 11 ft. just outside the power house, where there is another Y-connection, one branch for the generating unit and the other for the two pumping units. Each branch has a Venturi section for measurement of flows. Fig. 7 shows the general layout of the penstock.

Power Station Building. Like most modern power house construction, the substructure of Rocky River plant is built exclusively of concrete, with a small amount of steel work to support the lighter floors.

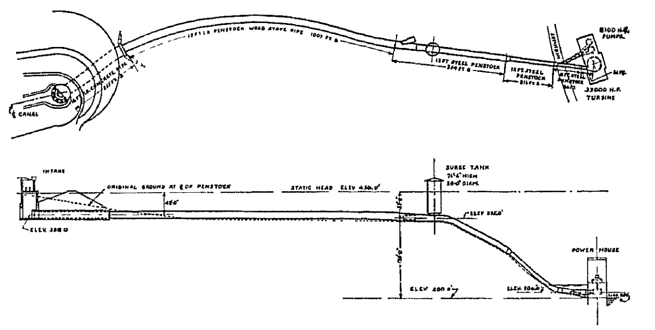


FIG. 7—PLAN AND PROFILE OF THE PIPE LINE AND PENSTOCK

The foundation rests on bedrock, which was so close to the elevation desired, that little rock had to be taken out or extra concrete put in. The concrete barrel type of construction was used, wherein the entire weight of generator, shaft, runner, and hydraulic thrust is carried through a concrete barrel and the turbine speed ring, to the foundations. The south end of the building, referred to as the switch bay, is supported on reinforced concrete columns. All the surface of the concrete substructure was coated with a water-proofing compound.

The power house superstructure is of structural steel framework and brick. Precast gypsum slabs provide the foundation for an asphalt built-up roof. All exterior trim of the building is of precast cement blocks.

There are four floors in the switch bay with a control cable terminal room below the first floor. The first floor is the control room with the switchboard. The second floor contains the 13,200-volt pump motor bus and switching, and the third and fourth floors are used for the 4600-volt distribution bus and storage battery room.

Hydraulic Equipment. The hydraulic equipment of the power station consists of one 33,300-hp. vertical shaft turbine and two 8100-hp. vertical shaft centrifugal pumps. A noteworthy feature of the turbine is the cyclinder gate which replaces the more conventional Butterfly or Johnson valves for directly shutting off the flow of water to the turbine. This cylinder gate is built in the turbine in the annular chamber between the pit liner and the speed-ring. It is operated from a valve on the generator floor which controls the admission of water under penstock pressure to the annular chambers above the valve. Positive mechanical locking devices hold the valve in either a full, open, or closed position.

The turbine is equipped with a 110,000 ft. lb. actuator governor located on the generator floor, arranged to operate the turbine gates by two cylinders in the turbine pit. Oil is supplied to the governor system at 200 lb. per sq. in. by an a-c. motor driven screw pump. The governor of this unit consists of a centrifugal speed element driven by a synchronous motor.

The centrifugal pumps, as far as I could find out, are the largest in the United States. The pump specifications called for a rating of 112,500 gal. per min. (250 cu. ft. per sec.) delivered against a maximum head of 240 ft. In the discharge line of each pump is a hydraulic cylinder operated Dow pivot valve. The intake to each pumping unit can be shut off by a self-closing Treadwell gate, and each intake is equipped with vertical trash racks with air raking device. Provision is made for the insertion of stop logs in each pump intake, and in the two openings of the turbine draft tube.

Electrical Equipment. The generator is of the standard vertical water-wheel type with shaft end exciter. It is rated at 30,000 kv-a., 80 per cent power factor, 13,900 volts, 3-phase, 60 cycle, 200 rev. per min., with direct connected exciter rated at 154 kw., 250 volts, compound wound with interpoles. The pump prime movers are vertical synchronous motors rated at 7900 kv-a., 80 per cent leading power factor, 13,200 volt (with voltage range of 5 per cent above or below) 3-phase, 60 cycle, 327 rev. per min. Pump motor and spare excitation is furnished by two motor-generator sets each consisting of a 150 kw., 1200 rev. per min., 250 volt, compound wound d-c. generator with interpoles direct connected to a 225-hp., 220-volt, 3-phase, 60-cycle, squirrel-cage induction motor.

The shaft of the generating unit is of two sections, one for generator and one for turbine, with forged half flanged sections bolted together upon installation. The turbine shaft has one guide bearing of the babbitted type mounted on the turbine crown plate. Lubrication is provided from a self contained gear pump driven from the main shaft. For emergency operation a float controlled rotary d-c. motor driven auxiliary oil pump is provided. The generator shaft has a Kingsbury thrust bearing with copper cooling coils and an upper and lower guide bearing of the babbitted type. The lubricating system for the generator shaft bearings consists of a gear pump, driven from the main shaft and located in the lower guide bearing oil pan.

The shaft of the pumping units is one piece forged steel with a Kingsbury combined upper guide and thrust bearing with copper cooling coils mounted on the upper spider designed to support the total weight and thrust; and a guide bearing between motor and pump, supported in a cast iron frame of heavy section bolted at the bottom to the upper head of the pump. Lubrication of all bearings on each unit is automatic

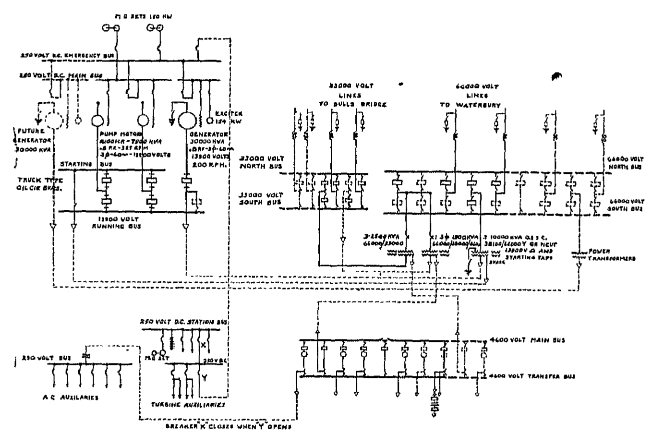


Fig. 8—Single-Line Wiring Diagram of Rocky River Plant

from a motor driven gear pump, with a similar pump for spare for each unit.

Station and Substation Equipment. Under this heading there are five distinct groups:

a. 4600-volt indoor local distribution bus

b. 33,000-volt outdoor tie-in bus for Bulls Bridge station

c. 66,000-volt outdoor main station bus

d. 13,900-volt indoor bus for pumps

e. Station service busses.

A single line wiring diagram, Fig. 8, shows the general arrangements.

a. The 4600-volt bus is for distribution of power to the New Milford district. It was installed in the Rocky River power station so as to bring it under the supervision and control of the Rocky River power plant operators.

b. The 33,000-volt outdoor bus afforded the most economical arrangement for connecting the Bulls Bridge station (upstream from Rocky River about 8 mi.) to 66,000-volt main transmission system. At the same time this bus provides the means for later distribution of power, at a voltage higher than 4600 volts, to the more remote points of the New Milford district.

c. The 66,000-volt outdoor substation consists of a main and a transfer bus with switching equipment for the two 66,000-volt 3-phase lines to Waterbury, the 30,000-kv-a. transformer bank stepping down to 13,900 volts and the connection to the transformer banks stepping down to 33,000 volts and 4600 volts respectively. Space was left in the bus structure so that each of these two banks can be equipped with a separate circuit breaker. The 30,000-kv-a. main transformer bank has two oil circuit breakers, one of which acts as transfer breaker. Although the generating voltage is 13,900 volts the main station voltage is 66,000 volts. If it were not for the two pumping units there would be no bus and no switching equipment at 13,900 volts. As a matter of fact the second generating unit will be connected directly to its transformer bank as indicated on the wiring diagram in Fig. 8. The 66,000 volt side of the 30,000-kv-a. transformer bank is *Y*-connected and solidly grounded. The 13,900-volt windings are provided with 40, 50, and 60 per cent taps to obtain with an open-delta connection, approximately half voltage for starting the pumps.

d. The 13,900-volt indoor substation as mentioned above is for the sole purpose of supplying power to the pumping units. There are two busses, a full voltage running bus and a half voltage starting bus. The connections from the transformer bank to the busses are made with single conductor cables. The generator leads are connected to the running bus through a set of disconnecting switches with provision for a future oil circuit breaker. On the generator side of this tap is a non-automatic oil circuit breaker to disconnect the generator from the transformer bank before it is used to supply power to the pumps from the 66,000-volt bus. The two oil circuit breakers connecting each pumping unit to the starting and running busses are interlocked.

e. Station Service Busses. A 230-volt, 60-cycle, 3-phase bus supplies power primarily to the two motor-generator sets, the battery charging set, the sump pumps, air compressor, station lighting, etc. The main 250-volt, d-c. or exciter bus is, at present, divided into two sections, one for the generator, the other for the two pumps. The 250-volt d-c. emergency bus is supplied from one of the two motor-generator sets. The governor oil pump and the emergency turbine oil pump are normally connected to this bus; if power fails they are automatically switched over on to the 250-volt d-c. battery bus. All the control circuits and small d-c. motors in the plant are connected to the battery bus. The control battery was purchased large enough so that it can perform the double function of control battery and storage battery.

The fact that the plant is a peak load plant and that the pumps can be shut down for short periods without serious consequences and further that the generating unit is never operated at the same time as the pumps, made it possible to eliminate many duplications and reserve equipment which otherwise would have been necessary.

Miscellaneous Equipment. Inasmuch as part of the substructure of the plant is always below the water level in the Housatonic river, a sump was provided to collect any water which might possibly leak or seep into the basement. The sump is also connected to the draft tube of the generating unit and the intakes of the two pumps. All connections to the sump are controlled by hydraulically operated valves. Two 500-gal. per min. pumps are used for removing the water from the sump. An air compressor and pressure tank supply the air for the station, including the trash rack raking devices and the surge tank previously mentioned. Flow meters are installed to measure the water from the pumps and the water to the turbine. The water levels at the canal intake as well as in tail-race are recorded. Watthour meters record the output from the generator, the energy used by the pumps and for general station use.

The Rocky River development was designed and built by the U. G. I. Contracting Company of Philadelphia for the Connecticut Light and Power Company in close collaboration with the engineering staff of the Connecticut Light and Power Company.

ADDITIONAL SUMMARY OF HYDRAULIC EQUIPMENT

Main dam. Length 952 ft., maximum distance from top to foundation 100 ft.

Earth fill. 367,800 cu. yd., 6 in. Wakefield core wall—31,000 sq. ft.

Canal dike. Length 2815 ft., earth fill, 332,000 cu. yd. 6 in. Wakefield core wall—52,000 sq. ft.

Canal. Length 3190 ft., excavation 708,200 cu. yd. Slope of sides generally 1 on 2 on cut side, 1 on 3 on dike side; Top elevation of dike 442 ft. Bottom 20 ft. wide at elev. 385 ft.

Danbury dikes. Earth fill, 59,000 cu. yd.

Lanesville gap dike. Earth fill, 18,000 cu. yd.

North Lanesville spillway. 175 cu. yd. concrete.

South Lanesville spillway. 742 cu. yd. concrete.

Wood pipe line. Approx. length 1007 ft., inside diameter 15 ft.; staves 4 in. by 6 in., tie rods 7/8 in. and 1 in. spaced 4 in. to 5 3/4 in.

Steel penstock. Approx. length 670 ft., inside diameter 13, 12, and 11 ft., thickness of steel plates 3/8 in. to 3/4 in.

Surge tank. Johnson differential type. Shell diameter 28 ft., shell height 76 ft., riser diameter 9 ft., riser height 73 ft., orifices 4 ft. 4 in. diameter and 6 ft. 3 in. diameter.

Dow pivot valves. Diameter 54 in.—hydraulic cylinder operated.

Sliding intake gate. Self closing Broome gate 18 ft. 6 in. by 18 ft. 10 in. Opening 16 ft. diameter.

Sliding suction intake gates. Treadwell gate 6 ft. by 7 ft.

Discussion

P. M. Lincoln: I should like to ask a question with regard to the last paper. There were certain figures which Mr. Amberg gave us on efficiencies reaching something over 100 per cent for certain conditions. I should like to ask whether or not those figures take account of evaporation. The matter of evaporation in a reservoir such as this where the water is stored over a period of years, must be a very important matter and must, of course, be considered carefully in the matter of calculating over-all efficiency. It strikes me the figures given are rather high, particularly if evaporation is to be considered.

J. D. Justin: I want to speak of Mr. Amberg's paper on the Rocky River Development. This development, due to its pumping feature, is entirely unique in America. However, in

Europe there have been some 35 or 40 plants that have been built along somewhat similar lines. One of these plants has a head of 540 ft., and there are two storage reservoirs. One of them is situated at the tail-water level and the other one forms the head-water with 540 ft. between them. The capacity of each reservoir is extremely small, only enough for daily operation. All this plant does at night when there isn't any peak load is to pump the water up in the reservoir at the top. Then over the peak-load period, the water comes down and goes through the turbines and produces energy on the peak of the load. The capacity of that plant is about 180,000 hp. There are 4 units, 45,000-hp. apiece. The pumps are somewhat larger than those at Rocky River and pump 640 cu. ft. of water a sec. each.

It seems to me rather remarkable that a plant like this, known as the Hengstey Plant in the Ruhr, Germany, would be economically justifiable in the heart of a coal region.

The capacity of the reservoir was less than 100,000,000 cu. ft.; in other words, about one-sixtieth of the capacity of the Rocky River reservoir.

I think there will be a good many more Rocky Rivers in America because there is an economic application for plants of this kind. In spite of all the advance in the steam plants, of mercury turbines and high-pressure units, there will still be some application for peak-load hydro plants where the cost of pumping for the high peak or the occasional peak would be a relatively small part of the alternate maintenance cost on the steam plant that would have to be provided to carry such peaks.

C. L. Cate: (communicated after adjournment) The Rocky River development goes further than the Swiss pumped-storage plants in that calculations have been based on using steam-generated power for pumping.

No data are given on the local storage at Bull's Bridge or Stevenson but with ordinary day-to-day pondage it is not clear how 50,000 kw. firm power is to be obtained from the three hydro plants as stated on the third page.

The author states that on the system of the Connecticut Light and Power Company there are no short-time peaks of any extent but that the system peak is the result of maximum 9-hr. day loads for which seasonal changes in load are responsible. This would indicate that during seasons of maximum load the load would be maintained at or near the peak for 9 hr. per day resulting in daily load factor of 37½ per cent on the hydro plants.

The 1914 hydrograph shows 6 months with an average run-off of about 0.3 cu. ft. per sec. per sq. mi. and 3 months with an average of 0.2 cu. ft. per sec. These figures would indicate maximum load factors of 20.4 per cent and 13.6 per cent respectively, at Bull's Bridge.

Corresponding figures for natural run-off at Stevenson would be 10.66 per cent and 7.1 per cent to which would be added water from the Rocky River plant operating at 37½ per cent load factor. This would increase the possible load factor at Stevenson by 13.6 per cent giving effective load factors of 24.26 per cent and 20.7 per cent which are both well below the 37½ per cent required. More water could be got to Stevenson by increasing the daily load factor at Rocky River but this would dissipate storage at a faster rate than allowed for in Mr. Amberg's calculations as given.

Fig. 5 shows on the lower curve representing present load a load factor of over 78 per cent for steam-generated power. If to this is added the steam required for pumping water the resulting load factor on the steam plant would apparently be over 90 per cent which seems somewhat high for a yearly load factor on steam equipment.

E. J. Amberg: In giving the figures for efficiencies and so forth, the very first thing we have done is to subtract from the run-off enough water to take care of evaporation. In other words, that 1,500,000,000 cu. ft. of water that we get in an average year from run-off is the net run-off after subtracting the run-off from 5 sq. mi. to take care of evaporation. We did that in order not to complicate the calculation of the studies afterward.

Now, I want to add just a few words to what I said before in the application of such storage reservoirs. There are some advantages that can't be put down in dollars and cents. One advantage is that you have a generating unit which is instantly available in case of breakdown of another unit on the system. In a steam plant, to do that you have to carry additional turbine capacity and additional boilers on the line, and even then you can't always put on the machine quickly enough to save the shutdown.

There is another feature in the development. I showed 50 per cent of the load carried by the hydro plant. That is the basis we used for figuring and making sure that there was enough water under the extreme condition. In other words, if we had a load of 100,000 kw. we have 50,000 kw. in hydro units, we have 50,000 kw., let me call it, in active steam units and then we have 10,000 or 20,000 kw. in reserve steam units.

Now, in actual practise we would not operate 50,000 kw. of hydro capacity. We would operate first our steam units. In other words, we operate that so-called spare steam unit and keep our reserve in the hydro which of course would give us more leeway on that limited 24-hr. firm hydro capacity that we had. Instead of running the hydro capacity down to 50,000 kw. we would only run it down to 60,000 kw. (Fig. 5) which would probably take off 30 per cent of the energy that was in the shaded area and leave that much as an additional safeguard on the pumping scheme.

We have now on our system in Connecticut a load factor of 50 per cent which gives a fairly large base for the upper half of the load curve (Fig. 5). On account of the high system load factor we are limited in application to a 50-50 ratio between hydro and steam capacity. If the load factor on our system were only 35 per cent we could then with the same amount of primary hydro energy available develop more than 50,000 kw. in capacity. In other words we could obtain a ratio of say 60 to 40 as between hydro and steam or even better than that. From this it can be seen that systems with a lower annual load factor than we have could make a better use of such a pumped-storage development because they could install more hydro capacity and to that extent increase the value of the development over and above the value which it represents on the Connecticut Light and Power Company system.

Mr. Cate in his discussion points out that for the extreme condition of maximum system load and minimum flow of water in the river the Rocky River Plant will have to be operated beyond the 9-hr. period in order to release sufficient water for the Stevenson Plant to produce its full share of the load. This statement for the extreme condition is correct but I should not call it a dissipation of storage and it certainly is not dissipated faster than allowed for in our calculations. In studying load curves we also find that the maximum hour occurs only once a year and that even for the day of maximum hour the 9-hr. average is considerably less than the maximum hour. We further find that the average of the other days in the week which had the maximum peak is considerably below the maximum peak so that the matter is not as serious as it would appear when assuming that this maximum peak condition continues throughout a week or more. The answer to this particular problem is the duration load curve shown in Fig. 5 which indicates clearly that the high loads do not and cannot occur very frequently because the load drops off rapidly.

The distinction I wanted to make is between having 15-min. or half-hourly peaks scattered over many days or to have the same equivalent energy concentrated in a maximum week of the year as is the case on our system.

On account of the high loads being "bunched" in our case it is necessary to store the water from one season of the year to another.

Our calculations absolutely were figured to take care of the most extreme condition. This most extreme condition will happen only once in probably 50 years because it will require a coincidence of maximum output week and maximum peak

load falling together; further it would require minimum river flow at the same time and it would further require that the reserve steam unit was out of commission. I have pointed out as one of the advantages of the hydro system the fact that under practical operating conditions the spare capacity would not be kept in the steam plant as assumed when making the study of this development but would be kept in the hydro plants and the spare steam unit would be actually used for daily operation. In this way the requirements on the hydro system would be very materially reduced.

Mr. Cate also questions the high load factor for the steam-generated power. In connection with this I simply want to call attention to the fact that this is the load factor of the power generated by steam but is not the station load factor because the reserve capacity is kept in the steam plant and if we compared the output of the steam plant based on 100 per cent use of its full installed capacity with the kilowatt-hours actually generated with the capacity actually required to carry the load we would obtain a station load factor which is considerably below that shown in the paper.

THE APPLICATION OF RELAYS FOR THE PROTECTION OF POWER SYSTEM INTER-CONNECTIONS[1]

(L. N. Crichton and H. C. Graves, Jr.)

New Haven, Conn., May 9, 1928

O. C. Traver: The pilot wire scheme has been given a reasonably clean bill by Messrs. Crichton and Graves, although it is clear that the only important objection thereto is the cost of the pilot conductors. The exceedingly prompt action in case of internal faults and freedom from tripping on any external trouble is winning increasing favor in spite of this handicap.

For the longer transmission lines, carrier current may be a solution to the problem, as, by its use, we may secure a similar result without the need of the auxiliary wires connecting the two ends of the line, and I will try to give a crude mental picture of the principle of the carrier-current scheme as we are interested in it at Schenectady, and as it is being tried out by the Ohio Power Company at the present time. The plate supply of the oscillator is taken directly from the current transformer and accordingly oscillation can occur only on the positive half wave, and is transmitted half the time, that is, on each half cycle. At the receiving tube, the plate supply is again taken from the current-transformer secondary so that current can only flow through it each half cycle and then only if the grid potential permits. This grid is controlled by the carrier from the far end with the result that the plate current flows only in case the instantaneous directions of the main currents at the two ends of the line are alike, thus indicating a sound feeder. Under these conditions, the over-current relays are simply restrained from functioning.

Should a fault occur on the protected line and the instantaneous directions at the two ends, therefore, be in opposition, the receiving tube plate current would not flow, and the over-current relays would be free to trip the breaker. If this line should be down, short-circuited, or broken, so as to prevent the passage of the carrier, then the failure of the carrier to appear at the receiving end would leave the over-current relays free to operate and thereby give complete protection.

In other words, by simply matching the instantaneous direction of the currents at the two ends of the line, we can tell whether the current going in is also going out at the same time, under which condition we say it is all right, or whether it is flowing inward from both ends, which is all wrong, or whether by chance it is going in one end and the other end is passing nothing, in which case we can, and do, take out the end carrying any current worth considering. We can secure operation within ¼ sec. This quick action is of great importance as all operating engineers know. (For a full description, see "*A Carrier Current Pilot System of Transmission Line Protection*, by A. S. Fitzgerald, A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928, p. 22.)

This paper indicates that many operating engineers hesitate about installing differential protection where many bushing-type current transformers must be connected in parallel in bus protection. Bushing transformers of the high ratio usually involved in such protection are generally as good as any.

I think there is no question of the more rapid action of balanced current protection as compared with impedance relays, so far as available equipment is concerned. Speed, again, is the important consideration, and balanced current relays have it. The impedance relay has a compensating advantage in that it can a little more simply care for the remaining single line.

The fault-detecting relay suggested by the authors involving two extra relays (over-current and undervoltage) does not seem as simple as one combining the two functions. Relays of the standard over-current type are available in which there is provided a voltage restraining action that simply changes the minimum operating current and leaves the time features as they were. This, of course, is in the nature of an impedance relay, but it is known by the descriptive name "Over-current-Undervoltage Relay." If, on a system, you need to care for a condition involving short circuits under light load conditions which are lower than the load currents at another time, this over-current-undervoltage relay will give the accustomed time characteristics but with a sliding current setting which is automatically adjusted by the system voltage.

In regard to the polyphase directional relay, I want to thank the authors for a very good defense of the practise which the General Electric Company has followed for some ten years back. We quite agree that the polyphase relay is a good one and hope they continue to make proper use of it.

I like the impedance-relay principle and believe more will be heard of it as conditions require, but the complication of Fig. 25 does not appear justified from any general point of view. Of the sixteen relay elements shown, the one ground relay can do from 90 to 95 per cent of the work. The table in Fig. 8, making its comparison on the basis of this unusual condition, is accordingly of very little value for the average system.

L. N. Crichton: Referring to Mr. Traver's discussion, the carrier-current relay protective scheme, which his company is interested in, is quite ingenious, and I am sure everyone is going to watch it with interest. It has a few disadvantages but so does every relay scheme, and I imagine it will be no harder, and perhaps easier to overcome those troubles than those of some other relay schemes.

The difficulty with bushing transformers for differential bus protection, mentioned in the paper, is something that has actually occurred on high-voltage transformers of a comparatively low ratio. There was quite a number of them in parallel, and it was found that if one of the transformers was dead, that is, the line was dead, the current from some of the other transformers would leak through it. Now, this was prevented in one case by putting auxiliary switches on the circuit breaker to cut out its transformer whenever the breaker was open. But this is bad because the switch may corrode or otherwise cause an open circuit and thus result in an unbalance which will cause improper operation.

There is not much doubt that any balanced relay will be a little faster than present impedance relays, but the difference in time will be small compared to the time required for the circuit breakers to open, that is, with present-day breakers. When making such comparisons it should be borne in mind that balanced schemes have their own troubles and objections.

Referring to the polyphase directional relay, there are not more than a half dozen systems in this country which demand its use. Most of the others can be served at least as well by the single-phase relay, maybe better.

All of us hope that there will not be many systems as complicated as that shown in Fig. 25 and Mr. Traver is correct in his statement that one of the relays shown will care for 90 to 95

1. A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928, p. 259.

per cent of the troubles. However, the remaining 10 or 5 per cent, or possibly less, must be cared for and the service is important enough to justify the extra relays. This installation is not the idea of one or two men but was chosen by a number of engineers intimately concerned with its success.

OSCILLOGRAPH RECORDING OF TRANSMISSION LINE DISTURBANCES[1]

(J. W. LEGG)

NEW HAVEN, CONN., MAY 9, 1928

M. A. Rusher: I should like to ask whether the twin vibrator element requires two air gaps in series or a single gap of greater width than that used with the standard vibrator element? Are the sensitivity and the natural frequency of this element the same as that of the standard oscillograph vibrator element?

I should also like to ask whether, in putting 15 records on one film, complication of records will not be introduced which will make it impossible to distinguish one curve from another?

It may be of interest in this connection that about ten years ago the General Electric Company built a 15-element oscillograph. The record used was over 12 in. wide and one of the main reasons for not building more of that type of oscillograph was that the records were difficult to read due to different curves running into each other.

I was also interested in the discussion with regard to the wattmeter elements for measuring power. For a number of years we have been using a three-phase oscillographic wattmeter for transmission-line tests. This instrument records the average power rather than instantaneous power as Mr. Legg's wattmeter element does, but it gives a record which is very easily read, one from which the average power at any instant can be obtained without calculation other than applying a single calibration. When operated in connection with other oscillographs we have found that the records from this wattmeter were of very great value.

Alexander Dovjikov: Setting aside the field of application of the cathode-ray oscillograph we feel that the requirements for automatic recording of system faults are satisfied to the greatest extent by the oscillographic type of instrument described by Mr. Legg. One of the most important features which makes these oscillographs particularly appropriate for the study of system transients is the introduction of oscillographic wattmeter elements—elements which measure power and power oscillations directly. A knowledge of the variations in this quantity is particularly valuable because it is the difference in power quantities that produce acceleration or deceleration of the machine rotors and eventually results in pull-out.

The combination of the flexible automatic features of the oscillograph equipment and the phase-sequence network for initiating and measuring quantities supplies the operating engineer with *quantitative facts* on which to base an intelligent analysis of the system operation. Interpreting the data obtained by reading the oscillograms, the necessary changes and adjustments in the system may be made; subsequent records would prove whether these changes and adjustments resulted in improvement.

J. W. Legg: I have been asked a number of questions about some of the details of the vibrator and other things. As to the twin vibrator galvanometer, used in the 3-Element Power Osiso and in the 15-element oscillograph, it has an air gap of 0.055 in. instead of the usual air gap of 0.030 in., still its sensitivity is twice that of the standard oscillograph vibrator, and it responds very well to 1000 cycles and thus beyond the range required for recording power transients. The sensitivity is more than one hundred times that of the Hall Recorder so that the power consumed is quite small.

As to 15 records on one film, I believe I limited that and said that in some cases 15 could be used. If the limit of speed is 10 in. in 10 sec., then 15 records would be quite confusing, especially if a very fine lens system were not used. However, on some of the tests we drive a 24-ft. film through in 4 or 5 sec. on which the cycles are spread way out, and then when 15 records are used, one can find every bit of the detail in every record. I have not seen any films yet with nine records in which one could not pick out every bit of the detail.

In three-phase lines, the three voltages will be just out of phase with one another, and even though they all have the same zero, each wave is perfectly free, provided you have a reasonable speed of film. Of course, 10 in. in 10 sec. would cause considerable confusion with 15 records. I have one lantern slide that appears to show some interference; however, the original record is clear.

Now, there is the question of the instantaneous wattmeter versus the average-value wattmeter. Our company carried on tests for a number of years with the average-value wattmeter, both polyphase and single-phase. We have made a small average-power polyphase wattmeter which one can carry in the palm of one's hand. But for the most part, the instantaneous values of power are much preferable. All galvanometers occupy about the same space and are freely interchangeable in these oscillographs.

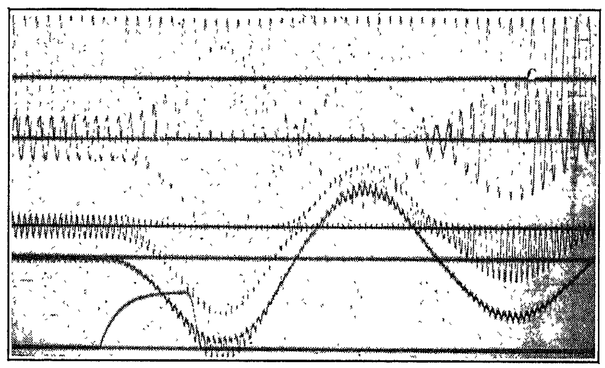


FIG. 1

In our 15-element oscillograph, the records are all in the same time-phase relation. This is not an improvised oscillograph. Previous ones were in reality a combination of several oscillographs, with one tier above the other, so that the light beams crossed at the cylindrical lens and reached the film half in one height and half in another, and thus gave a different time relation on the film. All fifteen of our records are in exact time-phase relationship, and easily controlled.

Many of the lantern slides shown when the paper was presented at New Haven were of oscillograms which were not available at the time the paper was written. The publication herewith of one showing a power surge recorded with a single-phase and polyphase instantaneous wattmeter should be more convincing than a lengthy written discussion.

The lower record is the short-circuit current of the d-c. end of a large motor-generator set. The one above this is of polyphase instantaneous watts, showing the surge of power from line to alternator, alternator to line, and so on. The record above that is single-phase instantaneous watts showing the changing power factor and kilovolt-amperes as well as giving a good idea of the surge of average power. The frequency here is twice that of the fundamental current or 120 cycles per sec. The record above shows instantaneous values of the a-c. in one line. The one above this, the top one, shows the instantaneous values of alternating potential in phase with the current when the power factor is unity. A comparison of the upper three waves will show the current lagging 90 deg. for zero power factor, lagging 180 deg. for minus unity power factor (when alternator is taking maximum power from line), and in phase with current when power factor is unity. However, the single-phase instantaneous watt curve tells a greater story than any other one record.

1. A. I. E. E. Quarterly TRANS., Vol. 47, No. 1, Jan. 1928, p. 135.

Symposium on Surge Voltage Investigations

Surge Voltage Investigation on Transmission Lines

BY W. W. LEWIS*

Member, A. I. E. E.

Synopsis.—This paper and companion papers discuss the surge voltage investigation on six power systems in the lightning season of 1927.

Valuable data have been secured as to the nature and polarity, magnitude, wave-front and attenuation of surges, also the effect of overhead ground wires, choke coils, and lightning arresters.

Especially interesting is the attenuation formula $A = k\ e^2$, the form of which indicates a close connection between attenuation and corona loss.

Further investigations are being carried on in the present year to secure more complete and exact data on wave shape and attenuation, effect of ground wires, lightning arresters, and choke coils.

IN 1926 the General Electric Company conducted a surge voltage investigation on a limited scale in cooperation with the Pennsylvania Power & Light Company, New England Power Company, and Consumers Power Company. Thirty surge-voltage recorders in all were used. In 1927 the investigation was continued with a larger number of instruments on the systems mentioned, and some additional systems were included, namely, the Ohio Power Company, Alabama Power Company, and New York Power & Light Corporation. In all 130 instruments were in service.

This investigation yielded a vast amount of data, which has been sifted and analyzed, and it is the purpose of this and the companion papers[1] to present the more important data and the conclusions to be derived therefrom.

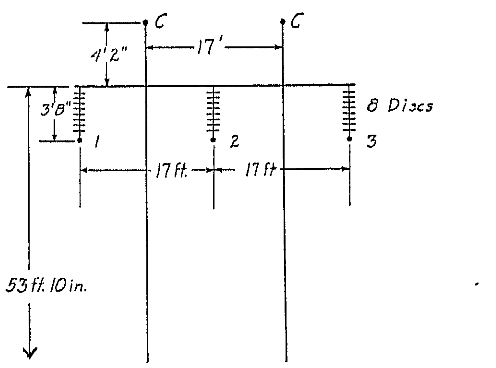


FIG. 1—DIAGRAM OF THE STANDARD TWO-POLE TOWER STRUCTURE USED ON THE LOCK 18—HATTIESBURG 110-KV. LINE OF THE ALABAMA POWER COMPANY

The wires marked *C* are the insulated communication circuits

The companion papers present in considerable detail a description of the system and the results of the investigation as far as the Pennsylvania Power & Light Company, New England Power Company, Ohio Power Company, and Consumers Power Company systems are concerned. The investigation on the Alabama Power Company and New York Power & Light Corporation's systems was not so extensive as on the other systems mentioned. Some data were obtained however, and these will be included in the present paper. A brief description of these two installations follows.

ALABAMA POWER COMPANY INSTALLATION

The 110-kv. transmission line extending from Lock 18 power plant in Alabama to Hattiesburg, Mississippi, was under investigation. This is a single-circuit line on wooden pole *H* frame construction, Fig. 1. The design characteristics of the line are given in Table I.

Fig. 2 shows diagrammatically the arrangement of the conductors and the communication wires. The communication wires are transposed between stations as indicated. They are insulated by means of porcelain pin type insulators, nominally rated 23 kv. The communication circuits terminate at the various stations in insulating transformers, with their mid-point grounded. The pins of the insulators of the communication wires, as well as the crossarms supporting the line conductors, are grounded at each tower.

TABLE I
DESIGN CHARACTERISTICS OF LOCK 18—HATTIESBURG LINE OF ALABAMA POWER CO.

Length	225 mi.
Type of construction	Wood pole, *H*-frame (see Fig. 1)
Height of conductors at tower	50 ft.
Configuration of conductors	Horizontal
Conductors	
Lock 18 to Meridian	297,500 cir. mils ACSR
Meridian-Hattiesburg	4/0 ACSR
Insulation	Suspension 8 disks OB-25622 Strain 9 disks OB-25622
Transpositions	None
Communication wires	½ in. steel and 1/0 ACSR (See Figs. 1 and 2)
Insulation of comm. wires	Pin type OB-12851
Transpositions of comm. wire	See Fig. 2

*General Electric Company, Schenectady, N. Y.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Fig. 2 also shows the location of the surge-voltage recorders. Fig. 3 is a typical surge-voltage recorder installation.

New York Power & Light Corporation Installation

A small portion of the 110-kv. and 33-kv. system of this company was under investigation. Fig. 4 shows

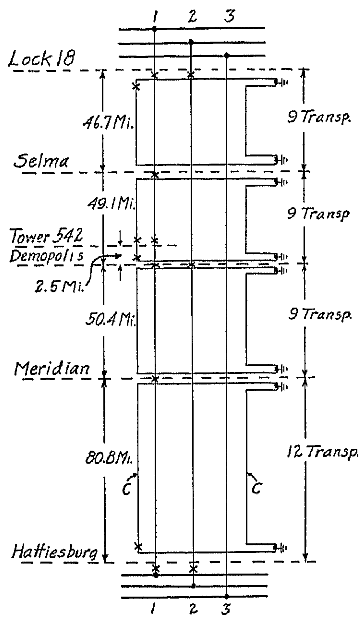


Fig. 2—Arrangement of Power Conductors and Communication Wires on Lock 18—Hattiesburg 110-Kv. Line of the Alabama Power Company

The power conductors are not transposed. The communication circuits are transposed frequently, the number of transpositions between stations being indicated on the diagram. To avoid confusion, the transpositions are not shown on the diagram. The location of the surge-voltage recorders is indicated by the symbol X.

TABLE II
DESIGN CHARACTERISTICS OF E-5 AND Q-95 LINES OF NEW YORK POWER & LIGHT CORP.

E-5 Line	
Operating voltage	110 kv.
Length	4.08 mi.
Type of construction	Double circuit steel towers
Ground wire	1 located at tip of tower
Insulation	Suspension 8 Locke 5800 disks Strain 9 Locke 5800 disks
Q-95 Line	
Operating voltage	33 kv.
Length	24 mi.
Type of construction	Part steel tower, double circuit Part wood pole
Ground wire	2 on steel towers 3/8 in. steel
Insulation	Steel tower, 8 Locke 5800 suspension 9 Locke 5800 strain Wood pole, 3 Locke 5800

this portion of the system and the location of the surge-voltage recorders. Table II gives the principal design characteristics. Fig. 5 shows a typical recorder installation.

Purpose of Investigation

The surge voltage investigation was conducted for

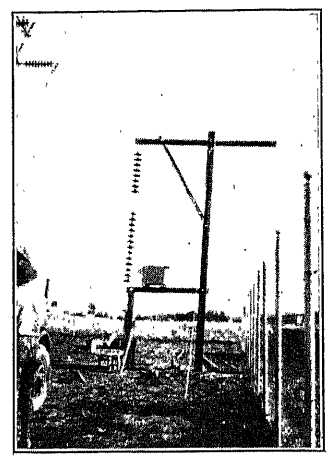


Fig. 3—Typical Surge Recorder Installation, Alabama Power Company

the purpose of securing information on the following subjects:

1. Nature and polarity of surges,
2. Magnitude of surge voltages on transmission lines due to lightning, switching, and arcing grounds,
3. Wave-front and wave-shape,
4. Attenuation of surges along the transmission line,
5. Effect of overhead ground wires in reducing surge voltages,
6. Effect of choke coils and lightning arresters.

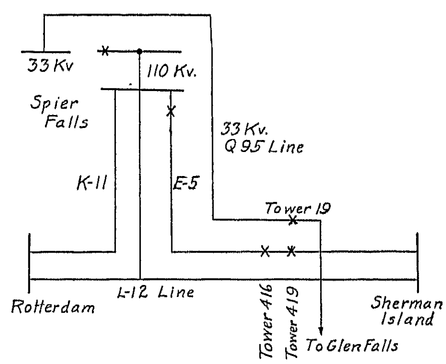


Fig. 4—Portion of New York Power & Light Corporation's 110- and 33-Kv. System

Surge-voltage recorder stations indicated by symbol *X*

Each of these items will be discussed in more or less detail.

1. *Nature and Polarity of Surges.*

Surges may be classified as unidirectional and oscillatory. The unidirectional surges may be positive or negative.

The oscillatory surges may be further classified as highly damped *H D*, medium damped *M D*, and slightly damped *S D*. A highly damped figure may be predominately positive or negative.

The *H D* figures are interpreted as being produced by

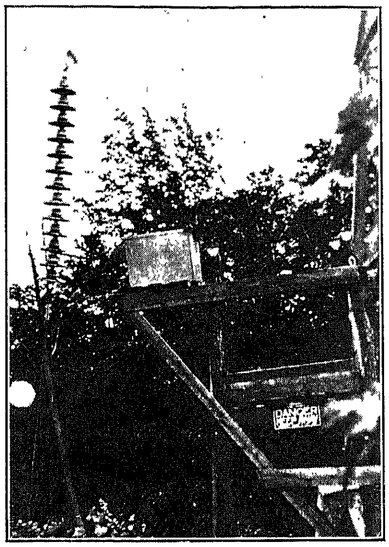


FIG. 5—TYPICAL SURGE RECORDER STATION, NEW YORK POWER & LIGHT CORPORATION

a surge voltage which lasts for only a few polarity reversals, say less than five.

The *M D* figures are attributed to oscillations following flashovers between line conductor and ground. They appeared in this investigation only on the Consumers Power system, which was the only isolated neutral system in the investigation.

The *S D* figures are of uncertain origin. They appear to be formed from a continuous application of a-c. potential for a duration of several seconds. They are thought to be connected with a particular potentiometer arrangement, as they did not appear when simultaneous records were taken with other potentiometer arrangements.

Examples of figures produced by the various classes of surges are given in Fig. 6 of this paper, and examples of *H D* and *S D* figures are also given in Lee and Foust's paper.[3]

Table III gives a summary of the lightning surges on the various systems classified as to polarity. All surges given as unidirectional were of the same polarity throughout at all stations where they were measured. Surge voltages given as oscillatory registered with both positive and negative polarity values at one or more stations, but many of these registered as unidirectional on some recorders. The generally low magnitude of the unidirectional surges shown by the table must be interpreted with this explanation in view. Unidirectional surges of high magnitude were obtained at some stations, but if the surge showed an oscillatory character at any other station, it was classed as oscillatory.

In the case of the New England Power Company a second classification is given in the table, in which the polarity is taken at the place where the magnitude of the surge was the highest. Classified in this manner the results appear somewhat different from the first classification.

The second classification is probably as reasonable as the first one. It is impossible in this study to separate the lightning surge from the switching surge which follows in case the line trips-out.

2. Magnitude of Surge Voltages on Transmission Lines due to Lightning, Switching, and Arcing Grounds.

TABLE III
POLARITY OF LIGHTNING SURGES

	Unidirectional				Oscillatory*						
	Positive		Negative		Positive		Negative		Equal		
System	No.	Times Nor.	No.	Times Nor.	No.	Times Nor.	No.	Times Nor.	No.	Times Nor.	Remarks
Ohio Power Co.	39	4.4	30	1.8							28 *HD*, max. 3.4 69 *SD*, max. 11.1 times normal
Pa. Pr. & Lt. Co.	2	10.0	3	1.9	11	11.7	11	11.6	21	11.6	
New England Power Co.	8	1.7	11	3.0	21	7.4	39	10.0	25	6.9	See note
Consumers Power Co.	1	1.9	3	1.2	28	8.4	20	7.5	24	10.0	
Alabama Power Co.	1	1.3	3	2.2	4	2.6	4	6.8	15	4.5	
New York Power & Light Corp.	14	1.8	10	1.7	13	2.3	15	6.9	19	7.3	All surges
Weighted total	65	234	60	120	77	559	89	807	104	864	
Average		3.6		2.0		7.25		9.1		8.3	
Note: If surges are classed as to polarity at place where magnitude of surge was highest, following will result:											
New England Power Co.	18	2.4	30	10.0	11	7.6	21	8.4	24	6.9	

*Classified as to whether surge is predominantly positive or negative, or with positive and negative equal.

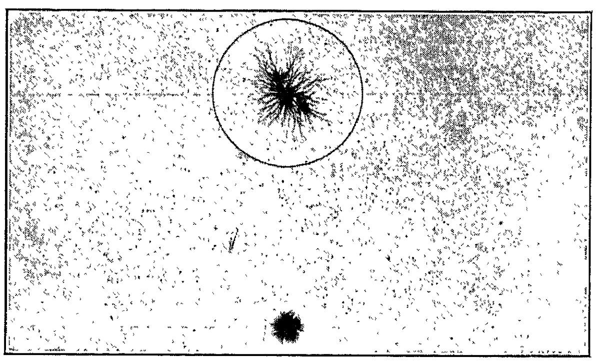
a. Lightning. In Table IV are listed the maximum voltages due to lightning, first, all figures and second, *H D* figures only. In this table are also listed the number of disks, type, and impulse flashover of the line insulators as determined in laboratory tests.[4]

It will be noted that the maximum voltage recorded in no case exceeds the impulse flashover values given, but is in most cases comparable in value or somewhat less. This would indicate that the impulse values given are fair values to use in estimating the lightning

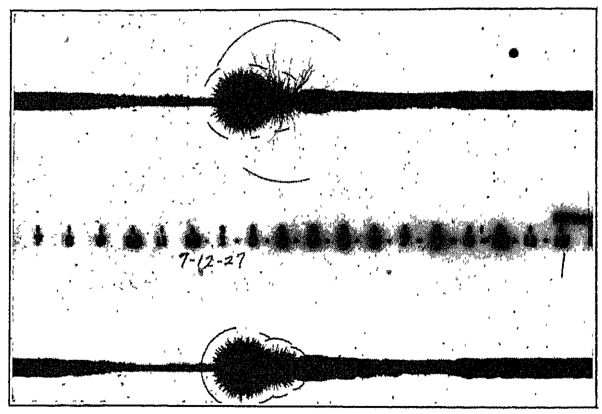
TABLE IV
MAXIMUM VOLTAGE DUE TO LIGHTNING

	Max. voltage		Line insulation			Ht. of line	
	All figures	*HD* figures	Disks	Type	Impulse flashover kv.	At tower	Average ht. top cond.
Ohio Power Co.	1200	475	10–11–12	OB–25622	1180–1400	60–73–86	70
Pa. Pr. & Lt. Co.	2100	1800	14–16	Locke 7500	1900–2140	66	50
New England Power Co.	900	900	8–9	OB-25620	1020–1120	49	40
Consumers Power Co.	1140 +	850	9 K–11 10 H–8	OB–25622	1080–1180	45–58–70 40–46–52	60
Alabama Power Co.	610	610	8–9	OB–25622	970–1080	50	40
New York Pr. & Lt. Corp.	660	620	8–9	Locke 5800	1150–1270	46–56–66	50

	Kv. per ft. of height	Kv. per ft. required to flash over insulators	Ratio kv. meas. to flash over kv. per cent	Normal voltage crest kv. to neutral	Maximum voltage no. times normal all figures
Ohio Power Co.	17	20	85	108	10.2
Pa. Pr. & Lt. Co.	42	43	98	180	11.7
New England Power Co.	23	28	82	90	10.
Consumers Power Co.	19	20	95	114	10.
Alabama Pr. Co.	15	27	55	90	6.8
New York Pr. & Lt. Corp.	13	25	52	90	7.3



A



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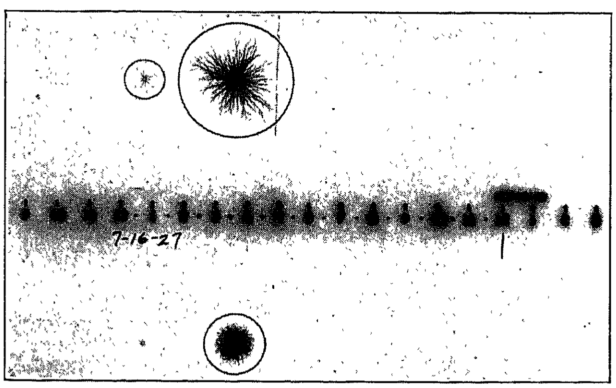

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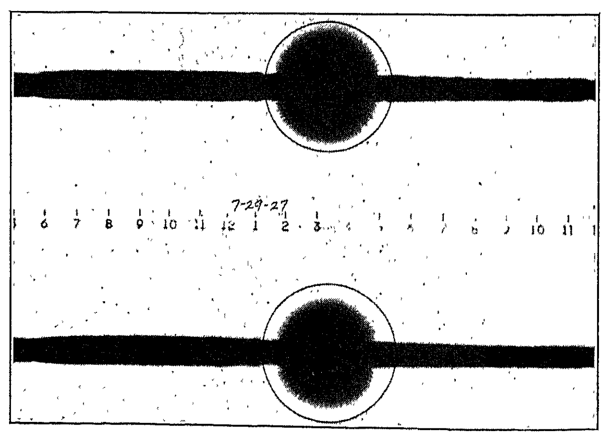

D

Fig. 6—Lichtenberg Figures Illustrating Various Types of Surges

a. Negative surge
b. Highly damped surge
c. Medium damped surge
d. Slightly damped surge

flashover of transmission lines, and would further indicate that the maximum voltage induced on a line is limited by the insulator flashover.

In this table are also given the height of the lines at the tower and an estimated average height of the top conductor, also the kv. per ft. of height based on the maximum voltage for all classes of figures. The kv. per ft. of height required for flashover is given, based on the

longest string listed. It will be noted in the last column of the table that voltages have been recorded from 52 to 98 per cent of the flashover value.

In most cases it is probable that the recorders were not located at the point of highest voltage. Also, it is possible that flashovers occur at much lower values than given in the table, which are based on a certain wave of very steep front. In practise the waves may be considerably less steep and otherwise different in shape.

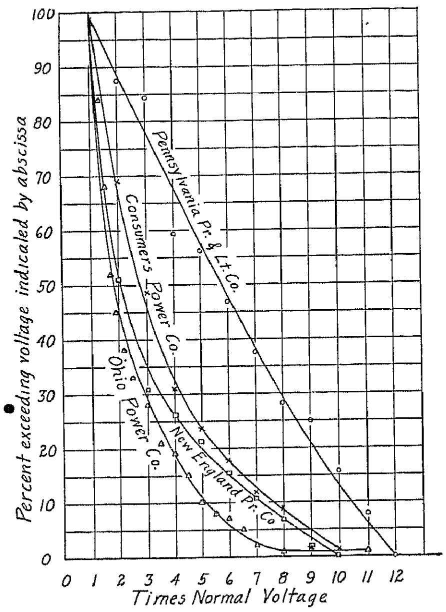

FIG. 7—MAGNITUDE OF SURGE VOLTAGES DUE TO LIGHTNING ON THE VARIOUS POWER SYSTEMS

Fig. 7 shows curves of surge voltages due to lightning for the various systems. In these curves the abcissas represent times normal crest to neutral volts, and the ordinates per cent of the total number exceeding the value indicated by the abcissas. All surges, *H D*, *M D*, and *S D*, have been grouped in these curves.

TABLE V
MAXIMUM VOLTAGE DUE TO SWITCHING

System	Normal voltage crest kv. to neutral	Energizing times normal kv.	Deenergizing times normal kv.	Both times normal kv.
Ohio Power Co.	108	4.2	5.2	
Pa. Pr. & Lt. Co.	180	4.0*	Less	
N. E. Pr. Co.	90	..	..	4.0
Cons. Pr. Co.	114	3.0	3.6	
Alabama Pr. Co.	90	1.5	2.6	
New York Pr. & Lt. Corp.	90	Less	3.4	
Average		3.2	3.7	

*On this system all switching was done on the low tension side.

It will be noted that the curves have the same general shape and that the majority of surges are of low value, *i. e.*, less than five times normal.

b. Switching. Table V gives the maximum voltages due to switching classified as to energizing and deenergizing lines.

It will be noted that deenergizing is slightly more severe than energizing.

Switching load on and off gives a very mild overvoltage disturbance, for example, 1.2 times normal on the Ohio Power Company's system.

The conclusions as to the relative severity of the various types of switching agree with conclusions arrived at previously with the oscillograph,[5] although the magnitudes recorded by the surge-voltage recorder are much greater than by the oscillograph.

In Fig. 8 are shown curves of switching surges for three systems, the abscissas representing the number of times normal and the ordinates representing percentage of all surges exceeding the given number of times normal shown on the abcissas.

It will be noted from these curves that the majority of all switching surges were less than three times normal.

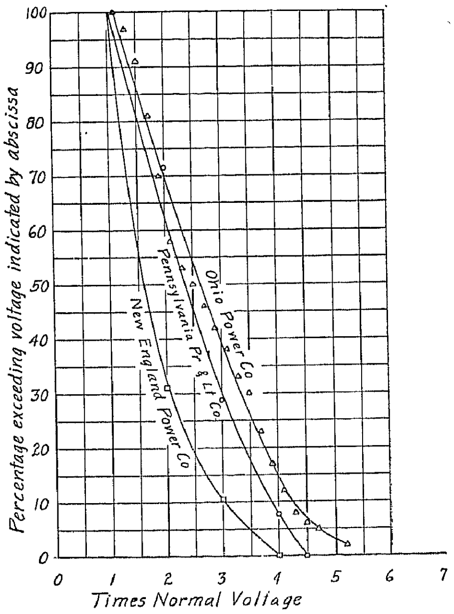

FIG. 8—MAGNITUDE OF SWITCHING SURGES ON VARIOUS SYSTEMS

In these surges *H D* figures predominated. They were very general throughout a system, that is, they appeared at all the recorder stations and at practically the same value.

c. Arcing Grounds. It is not possible from this investigation to separate lightning surges from the arcing ground or switching surges which follow in many cases. The initial surge caused by lightning and the subsequent surges due to arcing grounds or switching are shown as one surge by the recorder.

The Consumers Power Company is the only one of the systems operating with an isolated neutral, and therefore the only one subject to overvoltage due to arcing grounds. It is possible that the *M D* figures found only on this system were caused by arcing grounds. Pure *M D* figures were found of a magnitude of 7.7 times normal. Such *M D* figures recorded on practically all instruments on the system and in some

cases were coincident with switch trip-outs due to the operation of ground relays. In other cases the *M D* figures appeared coincidentally with system disturbances caused by arcing from the line wire to a tree. This incident accounted for five surges ranging from 2.5 to 3.6 normal times. Theoretically the maximum voltage that can be obtained from arcing grounds is about six times normal.[6]

d. General. From the data given it may be concluded that a transmission line insulated for about six times normal voltage, will be fairly safe from flashover due to switching or arcing grounds. The average system is insulated for this voltage or better.[6] The average system is also insulated for impulse voltages of 10 to 14 times normal.[4]

Since only a fraction of the voltages recorded reach the extreme value of 10 to 14 times normal on impulse (Fig. 7) and six times normal on switching or arcing

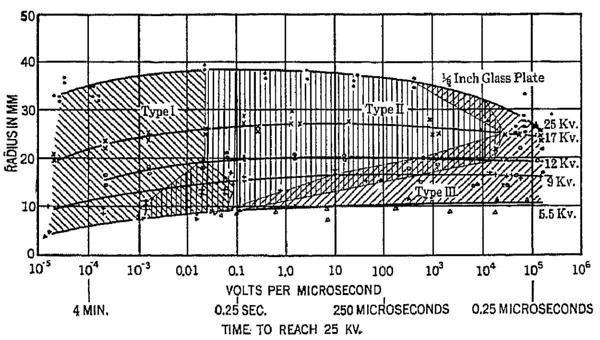

FIG. 9—CHART SHOWING VARIATION OF POSITIVE LICHTENBERG FIGURES WITH CREST VOLTAGE AND RATE OF VOLTAGE RISE, AND CLASSIFYING THE FIGURES INTO TYPES

grounds (Fig. 8), it would seem that most of the lines with average insulation should be fairly immune from flashover.

That many of the lines are not so immune indicates that our data on the line insulation may not be exact, or our data as to voltage magnitude not complete. Then again, we know very little about the behavior of direct strokes.

3. Wave-Front and Wave-Shape.

Up to the present time we have not been able to obtain any data on the shape of the waves encountered on transmission lines. Some data as to the front of the wave have been obtained by inspection of Lichtenberg figures. The method is as follows: The figure is examined as to type and magnitude. This locates the surge somewhere within wide limits by means of the chart, Fig. 9, reproduced from Mr. K. B. McEachron's A. I. E. E. paper.[2] If the surge appears at another station on the system, it may appear with a different magnitude and slope and perhaps be of a different type. Thus, it is possible by inspection of figures of the same surge appearing at two or more stations, to establish the time of the front within wide limits.

Mr. K. B. McEachron has examined the records of about 150 figures in this manner. The results of this study are shown in Table VI. It will be noted from this table that only one figure definitely indicated a front less than one microsecond, although some of those classed as less than 10 microseconds may also be less than 1.0 microsecond, likewise for those classed as less than 100 and 100,000 microseconds. Those classed as

TABLE VI
TIME OF FRONT OF WAVE AS INDICATED BY INSPECTION OF LICHTENBERG FIGURES

Time to reach crest in microseconds	No. of figures
Less than 1.0	1
Less than 10.0	1
Less than 100.0	11
Less than 100,000	44
At least 100.0	48
At least 10.0	16
At least 1.0	33
Total figures	154

at least 1.0 microsecond may be anything over 1.0 microsecond, even up to 10 or 100 microseconds.

From this indefinite grouping, we may make the following very rough summary as to the duration of wave-front: about 20 per cent between 1 and 10 microseconds, about 20 per cent between 10 and 100 and about 60 per cent over 100 microseconds.

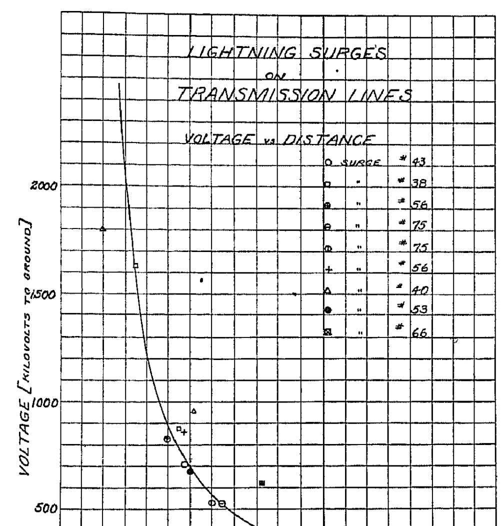

FIG. 10—CURVE SHOWING VARIATION OF VOLTAGE WITH DISTANCE FOR VARIOUS SURGES

Surges 38 and 40 are on Pennsylvania Power & Light Company's system, all others on New England Power system.

There is some indication from this study, that the waves of highest magnitude are also the steepest.

4. Attenuation of the Surges along the Transmission Line.

C. M. Foust and F. B. Menger have plotted a number of surges (Fig. 10) which appeared at more than

one station, with distance from an assumed origin as abscissas and voltage as ordinates. They then drew an average curve and determined equations for the variation of voltage with distance, and the rate of change of voltage with distance or attenuation. These equations are as follows:

$$e = \frac{e_0}{k\,l\,e_0 + 1} \tag{1}$$

$$A = -\,k\,e^2 \tag{2}$$

in which

e_0 = the initial voltage at the point where the surge originated

k = a proportionality factor which is found empirically

l = the distance in miles from the origin of the surge

e = voltage at any distance l

A = the attenuation in kilovolts per mile.

The factor k for all the surges investigated has been found to be about 0.00016.

These equations are used as in the following examples:

1. Assume the initial potential to be 2000 kv. Then at a distance 10 mi. from the origin:

$$e = \frac{2000}{(0.00016 \times 10 \times 2000) + 1} = 477 \text{ kv.}$$

The attenuation at the point of origin of the surge is

$$A = -\,0.00016 \times 2000^2$$
$$= -\,640 \text{ kv. per mi.}$$

2. If the initial surge was only 1000 kv. in magnitude, then the attenuation would be

$$A = -\,0.00016 \times 1000^2$$
$$= -\,160 \text{ kv. per mi.}$$

As a limiting case for any line, the flashover value of the line insulation may be taken as the initial voltage.

Equations (1) and (2) have a great deal of significance They state that the voltage varies inversely as the distance and that the attenuation varies as the square of the voltage. Since attenuation depends on resistance loss in the conductor and corona loss, and since it is known that resistance loss accounts for only a small amount of attenuation, the greater part of it must be due to corona loss. Corona loss varies as the square of the voltage, so that the attenuation, Equation (2), seems to tie in with the corona loss. The factor k probably varies with the size and spacing of the conductors on the transmission line, but for the various lines in this study the average of 0.00016 gave results which agree fairly well with the test data.

It seems likely that the particular units chosen for distance and potential have more effect on k than anything else. In our case we have used miles and kilovolts. If other units were used, such as absolute units, a different value for k would result. More data and more study may serve to refine this factor somewhat. Equations (1) and (2) are plotted in curve form in Fig. 11, assuming initial voltage e_0 = 1000 kv.

In this figure attenuation has been plotted for convenience as positive, although it will be noted from Equation (2) that it is a negative function.

The following example served as a useful check on the formulas: Surge No. 75 on the New England Power system gave readings at several stations. Assuming the voltage at the origin to be 1000 kv. (the estimated flashover value of the line insulators) the distance to the origin from one of the stations was computed and found to be 25 mi. Visual inspection indicated a flashover at 21.5 mi. from the station.

5. *Effect of Overhead Ground Wires in Reducing Surge Voltages.*

The ground wire data are rather inconclusive, mainly because of a lack of exact comparison between lines with and without ground wires, and also because of the effect of reflections. The surge-voltage recorder measures the maximum voltage regardless of whether the maxi-

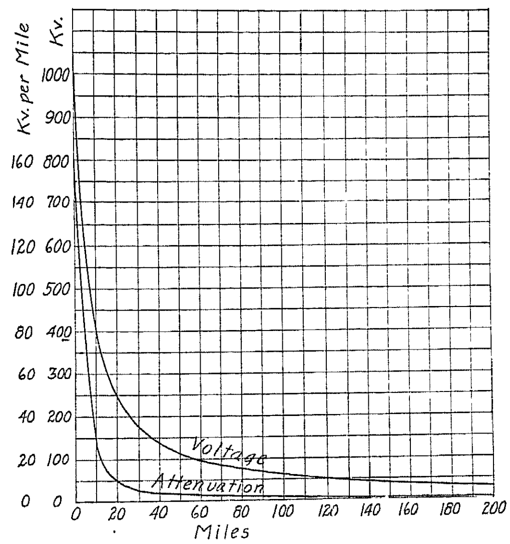

Fig. 11—Variation of Voltage with Distance and Rate of Decrease of Voltage with Distance, from Equations (1) and (2). Initial Voltage 1000 Kv.

mum is the initial voltage or the reflected voltage. Nevertheless the data have given a few indications of the effect of the ground wire.

a. Ohio Power Company's System. Approximately 50 surges were measured simultaneously on top, middle, and bottom conductors of the vertically arranged circuit. This line is a double circuit line with one overhead ground wire above and midway between the two circuits. In Table VII is given the theoretical potential of the three conductors without ground wire, expressed in per cent, on the assumption that the bottom conductor is 100 per cent and that the other conductors have potentials proportional to their heights above ground. Then there is given the theoretical potential with ground wire, still assuming that the bottom conductor is 100 per cent and using the protective ratios given in Reference 4, *i. e.*, 0.42, 0.52, and 0.62, for top, bottom, and lower conductors respectively. Finally is

given the average of the surge-voltage recorder readings expressed in per cent, with the bottom conductor as 100 per cent.

The order of the actual protection agrees with the theoretical, but is not so favorable as the theoretical based on ideal conditions. The results are illustrated graphically in Fig. 12.

TABLE VII
EFFECT OF OVERHEAD GROUND WIRE
OHIO POWER CO.

Conductor	Approx. height at tower—ft.	Theoretical potential without ground wire per cent	Theoretical potential with ground wire* per cent	Measured potential with ground wire. Average of readings per cent
Top........	85	143	68	89
Middle.....	72	121	84	98
Bottom	59	100	100	100

*Calculated by means of tables in Reference 4.

An instrument was placed on the ground wire at Tower 297. On this instrument 65 surges were recorded, the maximum of which was 8.2 kv. At the same time 380 kv. was recorded on a line conductor. This particular surge was due to lightning. Seventy per cent of all the surges were over 3 kv. Many of the surges were tied up with switching on the transmission lines.

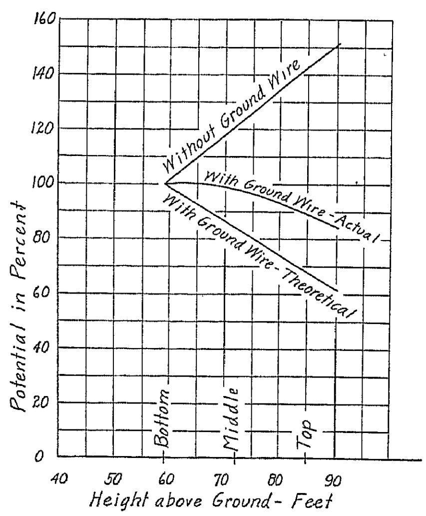

FIG. 12—GROUND WIRE PROTECTION, OHIO POWER COMPANY'S SYSTEM

b. Pennsylvania Power & Light Company's System. This 65-mi. line is equipped with 20 mi. of ground wire at the Wallenpaupack end and four mi. at the Siegfried end.

There were three periods of operation in 1927, (1) without ground wire, that is up to May 24, (2) period of installing ground wire, line not energized, May 24 to July 24, and (3) with ground wire, after July 24.

Any readings taken on the portion of the line not covered by ground wire are subject to reflection at the junction between the covered and not covered portions. Likewise the portions under the ground wire are subject to reflection at the terminals. All we can look for, therefore, is a tendency or trend.

For the period after the ground wire was installed a curve was drawn showing the highest values of surges recorded at stations along the line, and the average values of the surges recorded at the stations. The average of the highest values and the average of the averages were then taken for the unprotected portion of the line and for the protected portions. Table VIII shows the averages.

TABLE VIII
EFFECT OF OVERHEAD GROUND WIRE
PENNSYLVANIA POWER & LIGHT CO.

	Unprotected		Protected by ground wire: Wallenpaupack end		Protected by ground wire: Siegfried end	
	Times normal	Per cent	Times normal	Per cent	Times normal	Per cent
Average of highest......	7.1	100	5.6	80	7.4	104
Average of all values.......	4.4	100	3.6	82	4.0	91
Theoretical (two ground wires).......		100		35*		

*From reference 4.

c. New England Power System. On this system the transmission line under test consisted of two circuits horizontally arranged. The conductors may be designated 1, 2, 3, 4, 5, 6. There was one ground wire above and between conductors 2 and 3. Instruments were installed on all six conductors at two places, Griswoldville and Barre. The readings on these instruments did not necessarily indicate the potential due to the conductor position at that point, because the conductors were frequently transposed. The fairest attempt to evaluate the effect of the ground wire was to select those surges which had their highest values at one of the stations, and therefore presumably originated near that station. For this purpose five surges which had their highest value at Barre were selected. The readings are given in Table IX.

TABLE IX
EFFECT OF OVERHEAD GROUND WIRE—NEW ENGLAND POWER CO. SURGE VOLTAGES HAVING THEIR HIGHEST VALUE AT BARRE

Surge no.	Conductor position Number of times normal					
	1	2	3	4	5	6
59............	5.2	3.9	3.3	2.2	4.2	4.2
66............	9.0	3.9	6.5	3.8	6.0	6.1
88............	3.1	2.5	4.0	2.8	3.5	5.3
113...........	2.8	2.7	3.2	2.8	2.7	8.3
114...........	4.0	2.8	3.9	5.0	5.5	8.3
Average.......	4.8	3.1	4.2	3.3	4.4	6.4
Per cent.......	75	48	66	52	69	100
Theoretical per cent*........	74	64	64	74	89	100

*From Reference 4.
Ground wire above and between conductors 2 and 3.

It will be noted that these readings are not entirely consistent, sometimes one conductor being highest and sometimes another. The averages of the five surges are plotted in Fig. 13. The averages of the readings expressed in per cent agree fairly well with the theoretical protection to be expected.[4] Fig. 13 also shows the number of flashovers that took place in 1927 on the

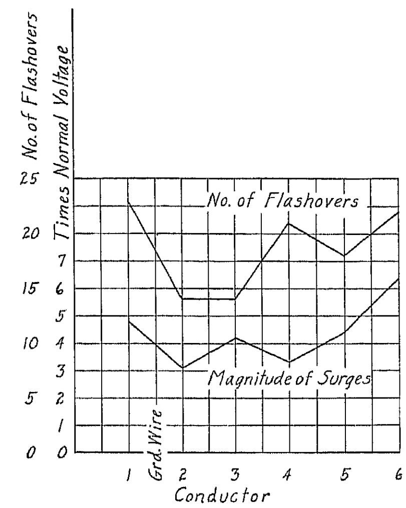

FIG. 13—POTENTIAL MEASURED ON VARIOUS CONDUCTORS AND FLASHOVERS OBSERVED, NEW ENGLAND POWER COMPANY

various conductors at all parts of the line, as indicated by a visual inspection. A somewhat irregular flashover curve is to be expected, because under the worst conditions the ground wire would only reduce the potential on the most favored conductors to about 2000 kv. and the other conductors would have higher potentials. This potential is about twice the flashover value of the insulators, and it is a matter of chance which conductor spills over.

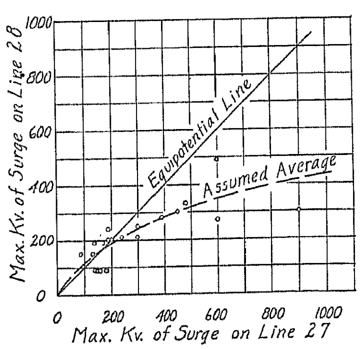

FIG. 14—GROUND WIRE PROTECTION, NEW ENGLAND POWER COMPANY, AS INDICATED BY READINGS AT GRISWOLDVILLE

Another effort to evaluate the effect of the ground wire has been made by plotting the highest crest value of lightning surges on line 27 (without ground wire) as abscissas and the highest values on line 28 (with ground wire) as ordinates. A reference line at 45 deg. is drawn to assist in interpreting the results. Fig. 14 shows the points plotted from the readings taken at Griswoldville and Fig. 15 at Barre. An average curve drawn through these points assumes a general drooping shape indicating the beneficial effect of the ground wire. This is more apparent on the readings at Griswoldville (Fig. 14) than those at Barre (Fig. 15).

d. Consumers Power Company. On this system there were two lines under investigation, the *H*-8 and *K*-11 lines between Saginaw River and Flint. These lines were on separate structures and in some cases as

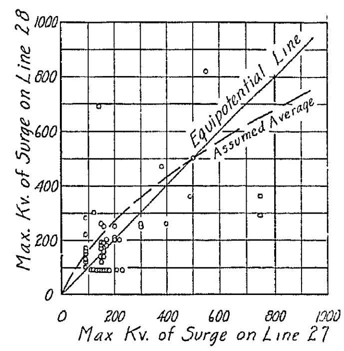

FIG. 15—GROUND WIRE PROTECTION, NEW ENGLAND POWER COMPANY, AS INDICATED BY READINGS AT BARRE

much as 10 mi. apart, being in multiple, however, at the two ends. During the entire season the *H*-8 line operated without ground wire while the *K*-11 had a ground wire during the latter part of the season.

For various reasons it is difficult to compare the performance of the *H*-8 and *K*-11 lines. Some of the reasons are: difference in tower height and configuration of conductors, difference in insulation, difference in size of conductor, also the fact that lines are tied together at ends and to other lines on which the trouble may originate. It is also difficult to compare the performance of the *K*-11 line before the ground wire was installed and after, because comparatively few high voltage surges were recorded, and very few of them before the ground wire was installed. About the only thing we can do is to compare the maximum potential on the two lines before and after the ground wire was installed, and also to compare the maximum obtained on the three conductors of the *K*-11 line before and after the installation of the ground wire. This is done in Table X. The results show a slightly lower maximum potential on the *K*-11 line after the ground wire was installed,

TABLE X
CONSUMERS POWER CO. HIGHEST POTENTIALS OBTAINED BEFORE AND AFTER GROUND WIRE WAS INSTALLED ON *K*-11 LINE

Line	Before ground wire installed times normal	After ground wire installed times normal
H-8	9	10
K-11	9	8
K-11 Top	8	6
Middle	9	8
Bottom	7.7	5.9

while at the same time the H-8 line, which had no ground wire, showed a slightly higher potential.

On the ground wire itself a number of surges was measured at tower 318 and midway between towers 318 and 319. The results of these readings are shown in Table XI.

In only one case was any potential indicated at the tower. The potential at the mid-span varied from 2 to something over 35 kv. All these potentials are small compared with the potential on the line conductor, and indicate that the ground wire is maintained near enough to ground potential to be effective in performing its protective function.

TABLE XI
CONSUMERS POWER CO.
POTENTIAL MEASURED ON GROUND WIRE
Kv. Crest

Surge no.	At mid-span towers 318 and 319	At tower 318	On conductor at tower 318
116	35 +	28	206
166	24	0	456
146	6	0	410
148.1	5.5	0	. .
87	3.7	0	850
94	2.	0	205

e. Alabama Power Company. As described previously, this is a single circuit line with conductors horizontally arranged and two lightly insulated overhead communication wires, which are connected to ground through transformers at the stations. Fig. 16 shows a comparison between the potential on the middle

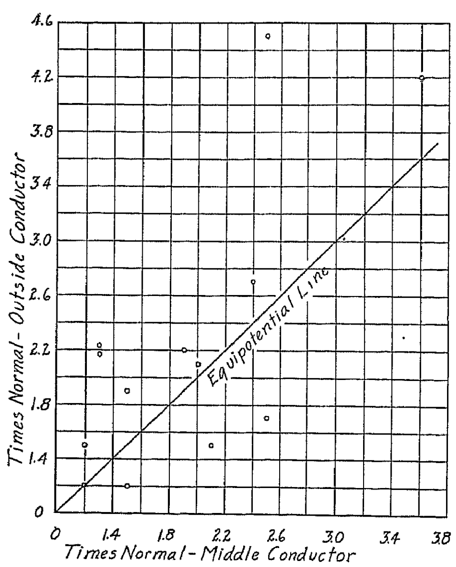

FIG. 16—COMPARISON BETWEEN POTENTIAL ON MIDDLE AND OUTSIDE CONDUCTORS, ALABAMA POWER COMPANY

conductor as abcissas and the potential on one of the outside conductors as ordinates. A 45-deg. line is plotted for reference. It will be noted that there are more points above the 45-deg. line than below, indicating that the outside phase is subject more to high voltage than the middle conductor.

On the insulated communication wire itself surges were recorded varying from 120 to 170 kv. As would be expected, these figures indicate that this wire is not kept as near ground potential as a wire which is connected to ground at each tower. Such an insulated wire should therefore not offer as effective protection as a wire more thoroughly connected to ground.

6. *Effect of Choke Coils and Lightning Arresters.*

At both ends of the Philo-Canton line, instruments were placed on the bus side and the line side of the choke coils on the top conductor.

Based on the average of ten simultaneous readings, the line side of the choke coil at Philo was 15 per cent higher than the bus side. At Canton the average of 12 readings showed the line side to be six per cent higher than the bus side.

It is not possible to say whether the surges originated on the Philo-Canton line or on other lines tied to the Philo or Canton bus. Assuming that they originated on the Philo-Canton line then the averages obtained indicate a small reflection of the incoming surges at the choke coils.

Surge-voltage recorders were placed across about 12 ohms resistance, installed in the ground or neutral end of the four-stack oxide film arresters at Canton, Newcomerstown, Philo, and Turner. Only two instruments gave records, those at Newcomerstown and Turner. Both switching and lightning surges apparently cause discharges, although the majority were tied in with lightning.

The current measurements varied from 150 to 2620 amperes. One reading was 1260 amperes, one 2620, and the balance were below 450 amperes.

On this system there were 97 highly damped lightning surges recorded. Of these only four were above two times normal. There were also 69 lightning surges classified as slightly damped, of which 31 were over three times normal and 18 over four times normal. Probably about three times normal is required between line and ground before the arrester gaps arc over, on account of the gap setting and the division of voltage between gap and arrester stack. The fact that only about one-fifth of all the surges recorded as due to lightning were over three times normal, and that not all of these were highest in the vicinity of the arresters, may account for the comparatively few readings of arrester discharge taken during the summer.

CONCLUSIONS

Some surge voltages due to lightning are unidirectional and some are oscillatory. Of the unidirectional surge voltages, some are positive and some are negative. Of the oscillatory surge voltages, some have positive characteristics predominating and some have negative.

While there may be a trend in some systems toward certain polarity characteristics, the surge voltages recorded on these systems are not exclusively of these

characteristics. It is certain that all unidirectional surge voltages of highest crest value are not of negative polarity, for several of positive polarity have been recorded. High-voltage surges of negative characteristics are in the majority however.

The oscillatory surges have been classified as highly damped *H D*, medium damped *M D*, and slightly damped *S D*. The *H D* figures are accepted without question. The *S D* figures are of doubtful origin.

The *M D* figures appeared only on one system, which operates with an isolated neutral. These figures reached a magnitude of 7.7 times normal and are thought to be associated with arcing grounds.

Surge voltages of the following upper magnitudes have been measured on the various systems:

Due to lightning, 7 to 12 times normal.

Due to switching, 2 to 5 times normal.

These values check those of previous investigations.[7]

It has been fairly well established that the voltage is limited by the flashover strength of the line insulators which on the average system is from 10 to 14 times normal[4] (normal equals crest value of line to neutral voltage).

Very little is known yet about the shapes of the waves encountered in lightning and other line disturbances. The wave-front varies through wide limits. Of 154 surges examined, about one-fifth had fronts between one and ten microseconds, about one-fifth between 10 and 100 microseconds, and about three-fifths over 100 microseconds.

An empirical formula has been derived for attenuation. This is of the form $A = k\,e^2$. That is, the attenuation is faster the higher the voltage. The form of this equation is similar to that for corona loss, $p = c\,e^2$, and indicates that the attenuation is due mainly to corona loss.

The study has shown the benefit due to overhead ground wire in some cases to be very small and in other cases to be almost up to the theoretical value. A conclusive study is very difficult to make, as it is almost impossible to obtain two lines of identical arrangement, in identical territory, subject to the same lightning conditions, and one with and one without ground wire.

The data as to the effect of choke coils and lightning arresters are meager and more information must be obtained along this line.

The data showed from 6 to 15 per cent difference of potential across the standard line choke coils.

Lightning arresters showed discharge currents varying from 150 to 2600 amperes.

In the present year efforts are to be made to obtain more complete and exact data on a few systems. A special effort will be made to obtain data on wave-shape, attenuation, effect of ground wires, and effect of lightning arresters and choke coils.

ACKNOWLEDGMENTS

The laboratory work in connection with this investigation was under the direction of Mr. E. S. Lee.

Acknowledgment is due C. M. Foust, A. L. Price, F. B. Menger, J. A. Tiedeman, R. F. McAtee, and others of the General Engineering Laboratory and J. B. McClure of the Central Station Engineering Department of the General Electric Company for their painstaking work in handling, analyzing, and correlating the large mass of data accumulated in this investigation. The hearty cooperation of the various power companies is also acknowledged.

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Discussion

For discussion of this paper see page 1147.

Lightning Investigation on New England Power Company System

BY E. W. DILLARD[1]
Associate, A. I. E. E.

Synopsis.—An analysis of the surges recorded during 1927 on a 75-mi. 110-kv. double-circuit transmission line of the New England Power System is presented in this paper. The surges are classified according to cause of surge-voltage damping, extent, etc. General conclusions are drawn regarding the nature of surges and protection afforded by ground wires.

Introduction

In long overhead transmission systems lightning disturbances constitute the greatest hazard to service. Perfect relay operation, even if it could be maintained, does not accomplish a complete cure, for usually system surges cause difficulties to a large number of users. Increasing standards of service emphasize the necessity of studies of lightning phenomena.

In making such studies on the New England Power

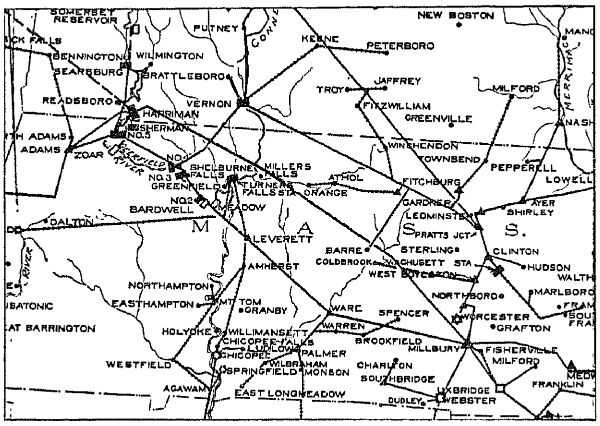

FIG. 1—PART OF NEW ENGLAND SYSTEM SHOWING HARRIMAN-MILLBURY LINE

System, we have considered that three general classes of information should be obtained.

1. Magnitude, extent, and character of lightning disturbances.
2. Protection afforded by ground wires.
3. Relative magnitude of surges of other than lightning origin.

Description of Line

In an effort to get information of this nature records have been made of the surges occurring on the 110-kv. line of this company extending from Harriman, Vermont, to Millbury, Mass., a distance of 74.6 mi. A map of part of the system showing the Harriman-Millbury line is given in Fig. 1.

This line was chosen for investigation because of its unusual construction features. The general type of construction is shown by Fig. 2. Horizontal arrangement was used to give better performance under sleet conditions, lessen the chances of arcs blowing from phase to phase, and to give a lower height of conductors above ground. A ground wire was installed over one circuit only. The characteristics of the line are:

Circuits	Two three-phase
Length	74.6 mi.
Operating voltage	110 kv.
Frequency	60 cycles
Insulator—suspension	8 disks
Insulators—strain	9 disks
Conductors	4/0 copper
Ground wires	One 7/16-in. crucible steel
Transpositions	Nine (three complete rolls)
Conductor spacing	12 and 13 ft.
Average height of conductors above ground (entire line)	42.15 ft.
Maximum elevation above sea level	2100 ft.

Surge-Voltage Recorder Installation

Through cooperation with the General Electric Company, surge-voltage recorders were installed and operated during the summers of 1926 and 1927. There was very little lightning in 1926 after the recorders were installed. During 1927 unusually severe lightning conditions were experienced and only 1927 surge-voltage records are discussed in this paper. Surge-voltage

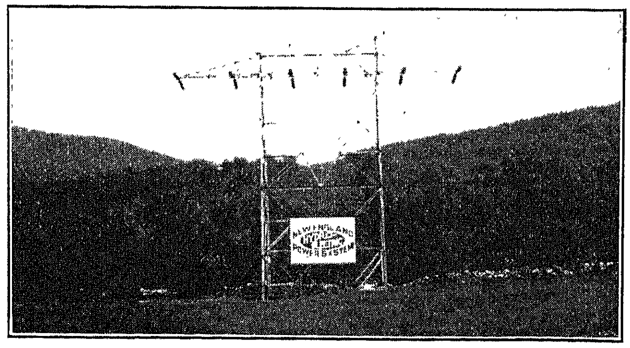

FIG. 2—TOWER ON HARRIMAN-MILLBURY 110-KV. LINE

1. Electrical Engineer, New England Power Company.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

records are supplemented by operating data of this and other years.

A total of twenty surge recorders was installed. Fig. 3 shows the location of the instruments. Three were installed on the north line at Harriman, six at the first intermediate station, two at the second intermediate station, six at the third intermediate station, and three on the south line at the Millbury station. Fig. 4 is a photograph of the installation at an intermediate station. Fig. 5 shows a typical record obtained.

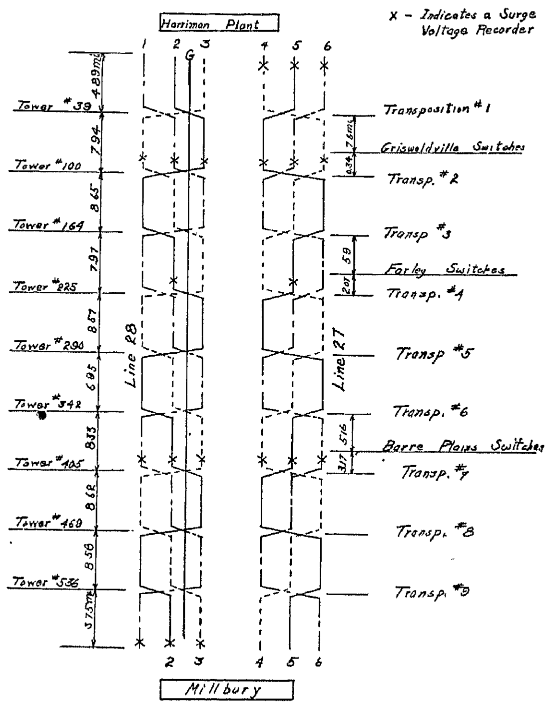

Fig. 3—Diagram of Harriman-Millbury Line

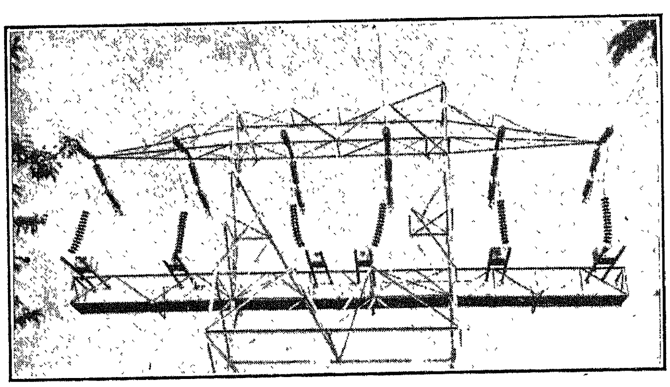

Fig. 4—Surge-Voltage Recorder Installation

Results

A total of 155 surge voltages was recorded between June 6, 1927, and October 10, 1927. These may be classified according to origin and maximum recorded voltage as follows:

Lightning	104	maximum 900 kv.
Switching	29	maximum 360 kv.
Unknown	22	maximum 270 kv.

Fig. 6 shows the number of surges recorded at various voltages. Only about 20 per cent of the recorded lightning surges were above 450 kv. No surge-voltage recorder indicated a high enough voltage to cause an insulator flashover, but during this period 47 trip-outs were experienced on the line. It is believed this observation indicates high decrement of lightning voltages rather than any inaccuracy of measurement.

Fig. 7 shows the number of surges at various voltages segregated according to amount of damping. The 104 lightning surges can be classified according to nature as follows:

Highly damped	71,	Maximum 900 kv.
Slightly damped	19,	Maximum 670 kv.
Highly damped and slightly damped, mixed	14,	Maximum 900 kv.

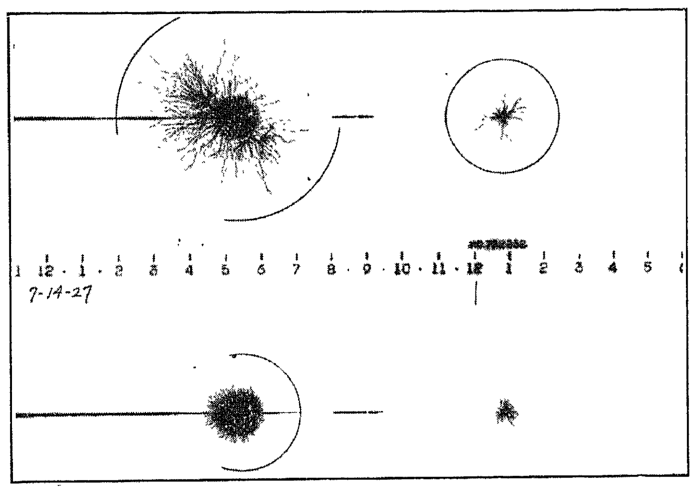

Fig. 5—Surge-Voltage Recorder Field Record

At left, large highly-damped figure from lightning, small slightly-damped figure superimposed. At right small highly damped figure from lightning.

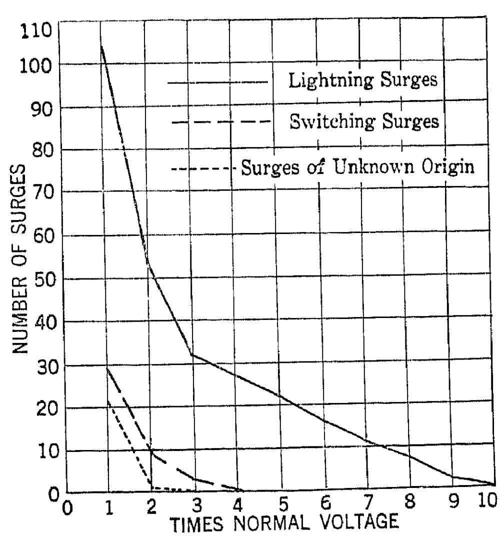

Fig. 6—Number of Surges of Different Origins which Exceed Various Times Normal Voltage Values

Cause of surge	No. highly damped	No. slightly damped	No. highly damped and slightly damped
Lightning	71	19	14
Switching	27		2
Unknown	10	12	

These results indicate a preponderance of highly damped surges both in regard to magnitude and to number. The inference to be drawn from this fact is that the surges most likely to cause flashovers are unidirectional. The origin of the slightly damped surges

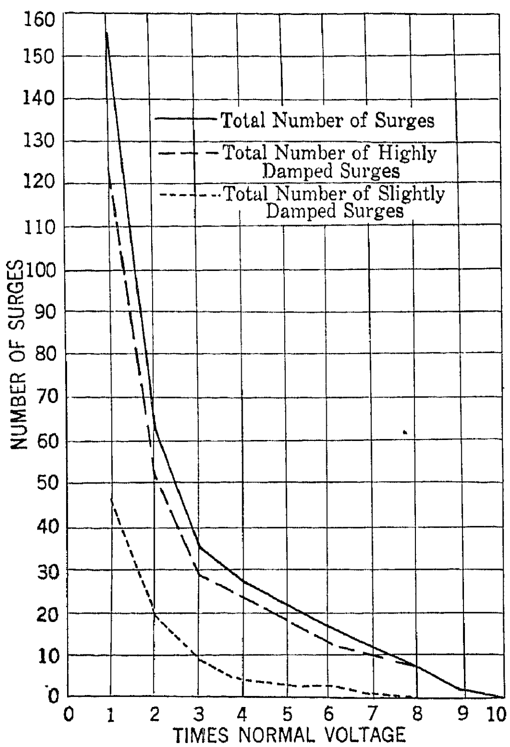

Fig. 7—Number of Surges at Various Times Normal Voltage

is not definitely known. There are indications that they are produced locally in the instrument by the potentiometer arrangement used. It is not felt that these records should be interpreted as indicating slightly damped surges on the line.

Protection of Ground Wire

It is not felt that the surge-voltage-recorder data in regard to ground-wire protection are particularly conclusive. Other operating data, particularly the record of flashovers, give a more conclusive indication of the value of ground wires. During the operation of the line, since 1924, there have been 57 flashovers in which only one line was involved. Forty-four of these flashovers have been on the unprotected line and 13 on the protected line. This would indicate a protective ratio for the ground wire of 3.4 to 1.

It is probable that the surge-recorder tests would have been more conclusive on this point if they had been more comprehensive. The information obtained in these tests is also confused by the fact that the lines are transposed.

Data from one of the intermediate stations, Barre, at which recorders were installed on all six conductors are shown in the following table. In order to eliminate the effect of transposition as much as possible, only those surges having their highest voltage at Barre are included as these surges probably originated near Barre

Surge Voltages Having Their Highest Value at Barre
Ground Wire is Above Conductors 2 and 3.

Surge No.	1	2	3	4	5	6
			Times Normal Voltage			
59	5.2	3.9	3.3	2.2	4.2	4.2
66	9.0	3.9	6.5	3.8	6.0	6.1
88	3.1	2.5	4.0	2.8	3.5	5.3
113	2.8	2.7	3.2	2.8	2.7	8.3
114	4.0	2.8	3.9	5.0	5.5	8.3
Average	4.8	3.1	4.2	3.3	4.4	6.4

and therefore their records were least affected by transposition. The ground wire at this point is above and between conductors 2 and 3.

It is seen that no definite conclusions as to the value of the ground wire can be drawn from these results.

Conclusions

1. On this system during the period of the investigations practically all surge voltages of appreciable magnitude due to lightning were unidirectional or highly damped and of negative polarity.

2. No switching surge of greater than four times normal was found.

3. The maximum voltage of a lightning disturbance does not seem to be impressed over more than a very limited portion of the line. More study should be given to this point.

4. The data collected by the surge-voltage recorder do not allow definite conclusions to be drawn relative to ground-wire protection. Other data from operating records indicate worth-while protection.

Discussion

For discussion of this paper see page 1147.

Surge-Voltage Investigations on the 140-Kv. System of the Consumers Power Company During 1927

BY J. G. HEMSTREET* and J. R. EATON*

Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.*—During the past four years, the Consumers Power Company has been making studies of surge voltages on its 140-kv. system in Michigan. Previous Institute papers have summarized the results of these investigations up to the end of 1926. This paper describes the system, outlines the studies made during the summer of 1927, and presents the results obtained during that season.*

INTRODUCTION

IN an effort to learn more of the electrical behavior of transmission lines, particularly under transient conditions, the Consumers Power Company and the General Electric Company conducted a cooperative investigation on the Power Company's 140-kv. transmission lines during the summer of 1927. Surge voltage recorders were connected to the lines at various points in order to measure the magnitude and time of occurrence of transient voltages. Data obtained from these instruments were correlated with system operation and disturbances as recorded in the load despatchers log.

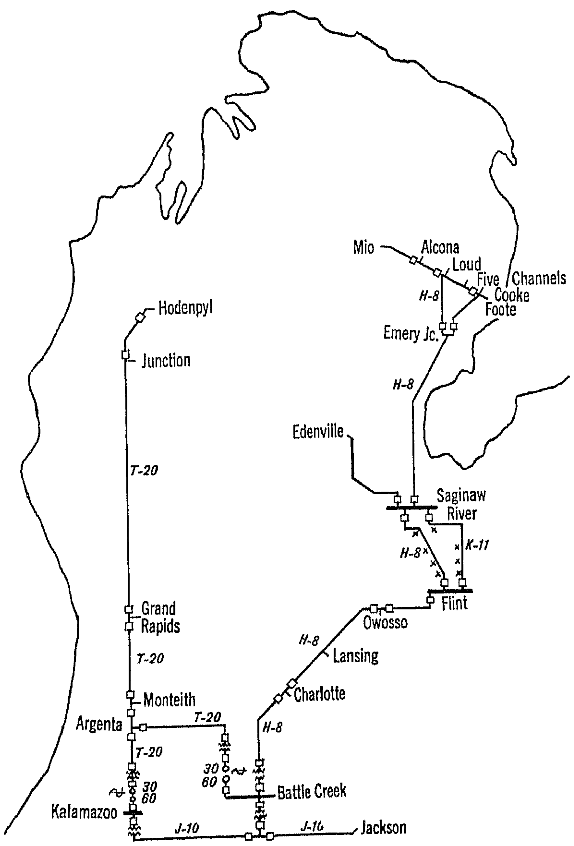

FIG. 1—CONSUMERS POWER CO., 140-KV. TRANSMISSION SYSTEM 1927

□ Oil circuit breakers
X Surge-voltage recorder stations

DESCRIPTION OF SYSTEM

The 140-kv. interconnected system of the Consumers Power Company is shown diagramatically on the map of the State of Michigan, Fig. 1. The system consists of three distinct parts interconnected through frequency changers and transformer banks:

1. The 140-kv., 30-cycle lines on the western side of the state from Hodenpyl Dam through Grand Rapids to Kalamazoo and Battle Creek. (Known as T-20)
2. The 140-kv., 60-cycle lines from Kalamazoo through Battle Creek to Jackson. (Known as J-10)

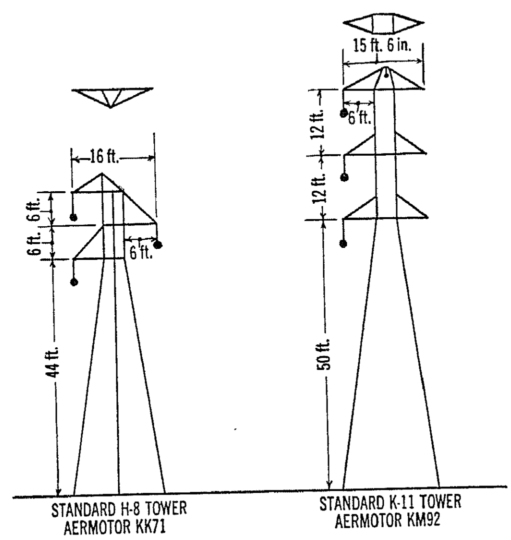

FIG. 2—STANDARD TOWERS

H-8 and K-11 lines

3. The 140-kv., 60-cycle lines from Mio and Edenville through Saginaw and Flint to Battle Creek. (Known as H-8, K-11, and Edenville)

The 140-kv. system is operated with isolated neutral throughout. Numerous spur lines of lower voltages feed from the various stations on the 140-kv. system.

TRANSMISSION LINES ON WHICH INSTRUMENTS WERE INSTALLED

The surge-voltage investigation was conducted on the H-8 and K-11 lines between Saginaw River Steam Plant and Flint. Under normal conditions, these two lines operate in parallel, being tied together at the

*Both of the Consumers Power Co., Jackson, Mich.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

substation buses. The design characteristics of these lines are shown in Table I. At the beginning of the summer neither line was equipped with a ground wire, but during the summer a ground wire was strung in place over the K-11 line. As these two lines are relatively close together, they are subjected to about the same storm conditions.

Eighteen surge-voltage recorders were installed on the

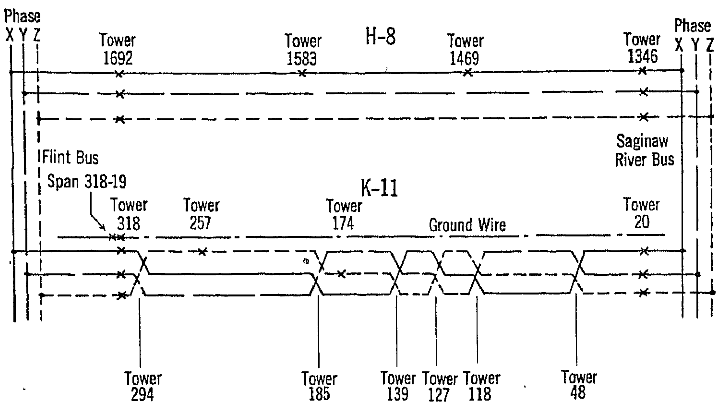

FIG. 3—TRANSPOSITIONS AND RECORDER LOCATIONS

H-8 and K-11 lines
X Indicates surge-voltage recorder

lines as shown by the diagram of Fig. 4. On each line, instruments were connected to all three phases at two towers, one of which was 2½ mi. from the Saginaw River Steam Plant and the other about 3½ mi. from Flint.

TABLE I
DESIGN CHARACTERISTICS OF H-8 AND K-11 LINES

	H-8	K-11
Length, miles	38	44
Type of construction	Steel tower	Steel tower
Type of tower	Aermotor KK-71 Single-circuit tower (see Fig. 2)	Aermotor KM-92 Double-circuit tower One circuit erected (see Fig. 2)
Height of top conductor at tower, ft.	52	70
Number of towers per mile	10	8
Configuration of conductor	. . .	⋮
Conductor[1]	115,000-cir. mil copper	3/0 copper (167,800 cir. mil)
Insulation[1]	10-OB No. 25,622 10-OB No. 10,566 mixed	9 OB No. 25,622
Arc protection[1]	None	OB flux control
Ground wire*	None	3/8 in. copper weld
Transpositions	None	See Fig. 3
Relays at Saginaw and Flint[2]	Trip-out on ground (CR)	Same
	Trip-out on overload (CZ)	Same
	Both directional	Same
Character of ground	Flat	Flat
Soil	Clay to sandy loam	Clay to sandy loam
Lightning arresters	Lightning arresters are installed at every station on the 140-kv. system except at Emery Jct. and Argenta. They are of various makes.	

*Ground wire on K-11 line strung in position between June 12 and August 14, 1927.

1. For references see bibliography.

Two additional recorders divided the intervening line into three approximately equal parts. At the tower nearest Flint on the K-11 line and in the middle of the adjoining span, surge recorders were installed to measure any voltage which might appear between the ground wire and the ground. Typical installations are shown in Figs. 5, 6, and 7.

SURGE-VOLTAGE RECORDERS

The surge-voltage recorder used in the investigation was a two-electrode instrument which measured all transients by positive Lichtenberg figures.[3] Connection to the line was made through a capacitance potentiometer consisting of a string of 15 standard suspension insulators, one end of which was connected to the line and the other end grounded. Instrument potential was obtained by a connection to the cap of the second insulator from the grounded end of the

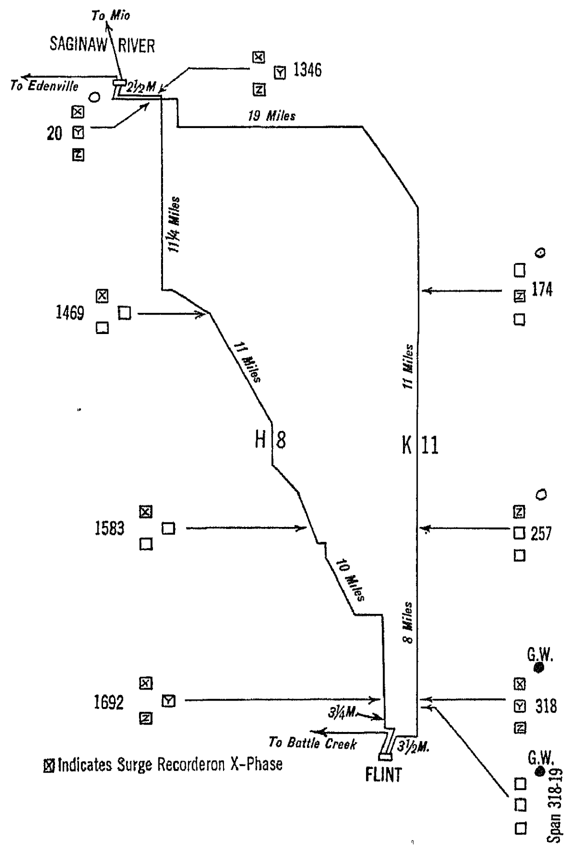

FIG. 4—LOCATION OF SURGE-VOLTAGE RECORDERS

H-8 and K-11 lines
Showing distances between stations

string. The recorders on the ground wire were directly connected, giving the same voltage on the instrument terminals as was built up on the ground wire.

DURATION OF THE INVESTIGATION

All surge-voltage recorders on the line conductors were put in service on May 31 and June 1, and those on the ground wire, on July 8, 1927.

On September 14, two instruments were stopped,

and on September 20 and 21, the remaining recorders were taken out of service.

Results

During the period of the investigation, 219 surge voltages, classified as to origin as given in Table II, were recorded.

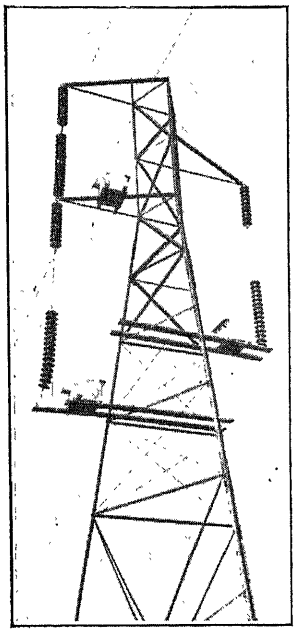

Fig. 5—Typical Surge Recorder Installation

H-8 line

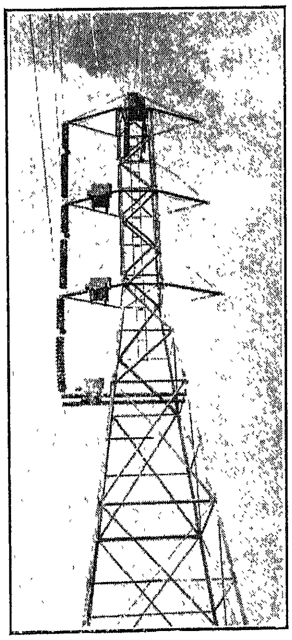

Fig. 6—Typical Surge Recorder Installation

K-11 line

Showing recorder connected to ground wire

Surge Voltages Due to Lightning

Number and Magnitude. During the investigation, 76 surge voltages, which were attributed to lightning, were recorded. The number of these surges, exceeding various times normal values, is shown by the curves of Fig. 8. It will be noted that only 20 per cent of the recorded voltages exceeded five times normal. (570 kv.)

Polarity. Surges voltages attributed to lightning are classified as to polarity in Table III.

These data indicate that all lightning surge voltages of appreciable magnitude on this particular system were oscillatory during the period of the tests. This statement cannot be made as a definite conclusion because of several factors among which are:

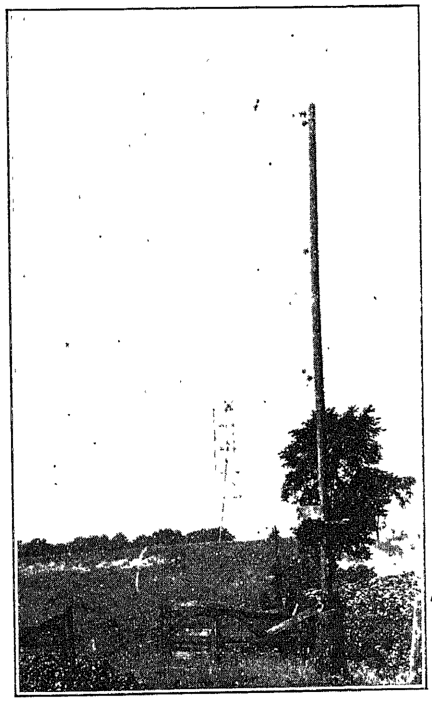

Fig. 7—Surge Recorder Installation at Mid-Span of Ground Wire

K-11 line

TABLE II
CLASSIFICATION OF SURGE VOLTAGES

Origin	Number	Highest crest value	
		Times normal	Kv.
Lightning	76	10.0 +	1140
Switching	93	3.3	375
Accidental short circuits and grounds	1	3.6	410
Unknown	49	5.7	640
Total	219		

Note: Normal crest voltage to ground = 114 kv.

1. The possibility of reflections with reversed polarity of voltage.

2. Possibility of secondary oscillatory surges resulting from circuit-breaker operation.

3. Because of limitations of the instrument, two unidirectional surges of opposite polarity, occurring

with little intervening time interval, record as one oscillatory surge voltage.

Nature. Lichtenberg figures of three different natures were recorded by lightning surge voltages: highly damped (H. D.), medium damped (M. D.), and slightly damped (S. D.). The highly damped figures are interpreted as having been produced by surge voltages which were of extremely short duration, lasting for only a few polarity reversals. The medium damped figures are produced by surge voltages which are less rapidly damped and may last for an appreciable length of time. Such surge-voltage registrations in almost every case correlated with arc-over from line conductor to ground and with automatic circuit breaker operation. These medium damped figures apparently are peculiar to the isolated neutral system, and are probably produced by line oscillations following flashover. The slightly damped figures are of uncertain origin and seem to be dependent upon the type of potentiometer with which the surge recorder is connected to the line. In view of this uncertainty, conclusions drawn from slightly damped figures are open to question. Continued laboratory studies should lead to an accurate interpretation of the slightly damped figures. The number and magnitude of lightning surge voltages under the above classification are shown in Table IV.

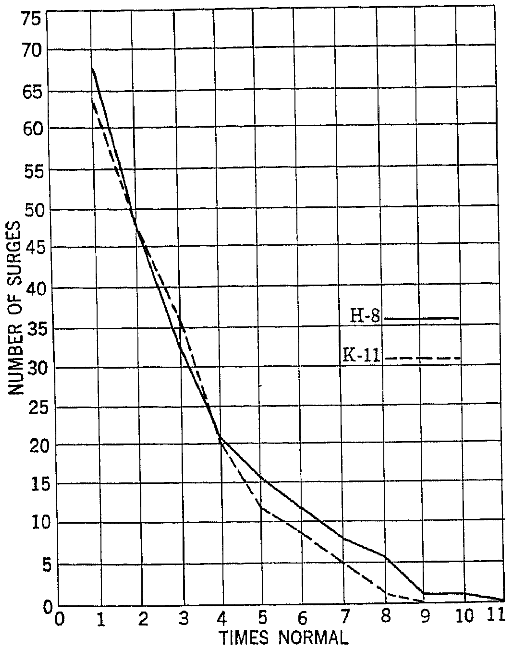

FIG. 8—NUMBER OF LIGHTNING SURGE VOLTAGES EXCEEDING VARIOUS TIMES-NORMAL VALUES

Entire season
H-8 and K-11 lines

TABLE III
POLARITY OF LIGHTNING SURGE VOLTAGES

Polarity	Number	Highest crest value	
		Time normal	Kv.
Unidirectional			
Positive....................	1	1.9	216
Negative..................	3	1.2	137
Oscillatory			
Highest crest value			
Positive.................	28	8.4	960
Negative................	20	7.5	855
Positive and negative crest values equal...........	24	10.0 +	1140 +

TABLE IV
NATURE OF LIGHTNING SURGE VOLTAGES

Nature	Number	Highest crest value	
		Time normal	Kv.
H. D.......................	13	7.5	855
M. D.......................	10	7.7	877
S. D.......................	16	7.8	890
H. D. M. D. mixed...........	12	7.1	810
H. D. S. D. mixed...........	7	7.3	832
M. D. S. D. mixed...........	11	8.8	1000
H. D. M. D. S. D. mixed......	7	10.0 +	1140 +
Total.................	76		

Surge voltages which were recorded by highly damped or slightly damped figures were very similar as regards magnitude and extent over the transmission system. In almost all cases such disturbances were confined to less than 20 mi. of line. The magnitude of surge voltages recorded by medium damped figures was slightly less than the magnitude of those producing highly damped or slightly damped figures, but they were quite different in that they recorded with almost equal value at all instrument locations.

Attenuation Along the Line. As pointed out above, surge voltages of medium damped characteristics are recorded with almost equal magnitudes at all recorder stations, and hence show practically no attenuation along the line. Surge voltages recorded by either slightly damped or highly damped figures showed considerable reduction in magnitude from one instrument station to the next. Surge voltages of the highly damped type in some cases reduced from 250 kv. to 0 kv. in 10 mi., or at the average rate of 25 kv. per mile. Those recorded by slightly damped figures, in some cases reduced from 900 kv. to 300 kv. in 10 miles, or at an average rate of 60 kv. per mile.

Comparison of insulator flashover to surge voltage recorder data showed that in some cases the voltage reduced from a value sufficient to cause insulator flashover (about 1000 kv.) to 500 kv. in distances of 4 to 10 miles. This indicates average reductions in voltage between 50 and 125 kv. per mile.

Protective Value of the Ground Wire. During the investigation, a ground wire was strung in place over the K-11 line, making possible a study of the operation of this line with and without a ground wire, and a comparison of its performance to that of the H-8 line which has no ground wire. Fig. 9

shows the number and magnitude of surge voltages recorded on the H-8 and K-11 lines before the ground wire was completely installed on the K-11. These curves indicate that during that period, the voltages recorded were about equally severe on the two lines. The curves of Fig. 10 show the number and magnitude of the surge voltages recorded after the ground wire was installed. It will be noted that during this period, the recorded surge voltages were considerably less severe on the K-11 than on the H-8.

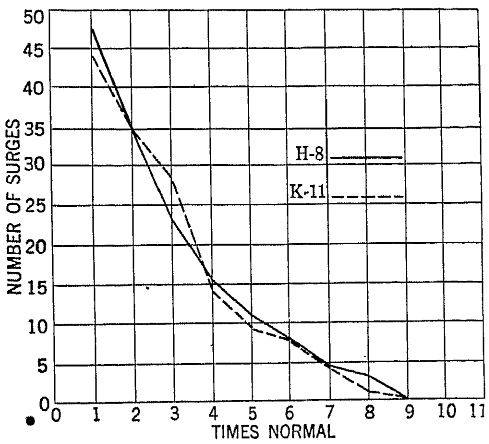

FIG. 9—NUMBER OF LIGHTNING SURGE VOLTAGES EXCEEDING VARIOUS TIMES-NORMAL VALUES

Before ground wire was installed on K-11 line

Relation of Conductor Height to Voltage Measured. The curves of Fig. 11 and 12 show the magnitude and number of surge voltages recorded on the top, middle, and low conductors of the H-8 and K-11 lines, respectively, using only the data obtained at those stations where instruments were installed on all three conductors. From these curves, it is seen that no definite relation exists between the magnitude of surge voltages measured and conductor height. It is thought that transpositions in the line, reflection of the transient waves, and other factors, so complicate this study that voltages measured at a few recorder stations do not give a true indication of the relative voltages induced at the origin of the lightning disturbances.

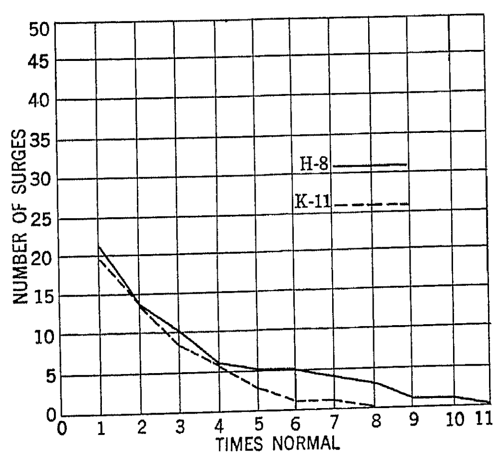

FIG. 10—NUMBER OF LIGHTNING SURGE VOLTAGES EXCEEDING VARIOUS TIMES-NORMAL VALUES

Ground wire on K-11 line

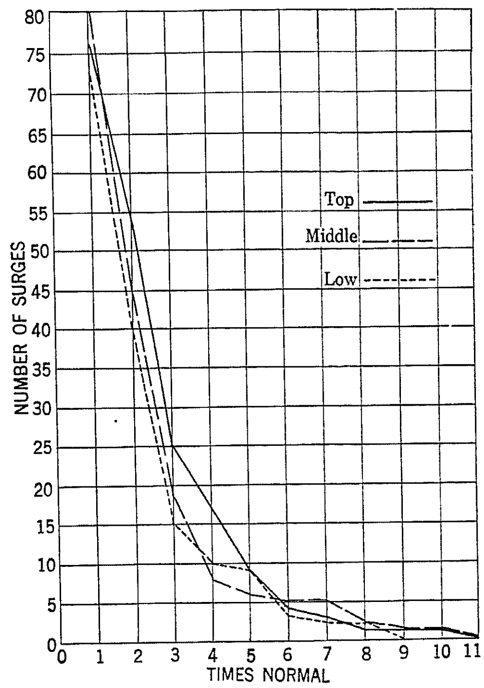

FIG. 11—NUMBER OF LIGHTNING SURGE VOLTAGES EXCEEDING VARIOUS TIMES-NORMAL VALUES, RECORDED ON TOP, MIDDLE, AND LOW CONDUCTORS

H-8 line

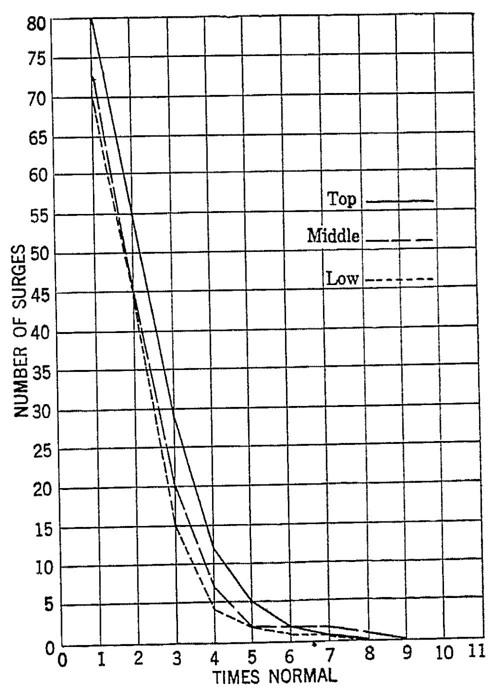

FIG. 12—NUMBER OF LIGHTNING SURGE VOLTAGES EXCEEDING VARIOUS TIMES-NORMAL VALUES, RECORDED ON TOP, MIDDLE, AND LOW CONDUCTORS

K-11 line

Surges Coincident with Switch Trip-Out. In every

case of switch trip-out on the 140-kv. system, surge voltages were recorded at one or more of the surge recorder stations. Trip-outs of the H-8 or K-11 lines between Saginaw River and Flint produced registrations on practically all instruments in operation. In some instances, the recorded voltages were low (400 kv.) as compared with the generally accepted value of insulator flashover (approximately 1000 kv.). However, it is reasonably certain that in such cases, the lightning discharge took place at a point on the line some distance from a recorder station, and the voltage wave attenuated considerably before reaching the first instrument. The transient recorded at the various instrument stations was probably the result of the arcing ground or of circuit breaker operation, rather than of the voltage disturbance set up by the lightning itself. The figures recorded at the time of switch trip-outs were predominately of the nature designated as medium damped, although also highly damped and slightly damped figures were frequently recorded.

Surge voltages not coincident with switch trip-outs were for the most part very local in extent, of values from 1 to 10 times normal (114 to 1140 kv.) and of all three figures types with those of highly damped and slightly damped characteristics predominating.

Surge Voltages on the Ground Wire. Table V shows the lightning surge voltages recorded on the ground wire at mid-span and at the tower, and

TABLE V
LIGHTNING SURGE VOLTAGES ON GROUND WIRE

On ground wire		On conductor
At mid-span 318-319 Kv.	At tower 318 Kv.	At tower 318 Kv.
+35+	+28	+206 −160
+24 −16	0	−456 +285
− 6 + 4	0	−410 +285
+5.5	0	Record obscured
−3.7	0	−850 +182
+2.0	0	+205 −160

the highest value recorded on either of the line conductors at the same tower.

The data show that a much higher value of voltage may appear on the ground wire at mid-span than at the tower, possibly due to the finite length of time required for the transient to travel along the wire to ground at the tower.

Line Failures. During the operation of the surge recorders lightning caused failure of the H-8 line about 50 mi. southwest of Flint when an insulator flashover burned off one of the conductors, permitting it to short-circuit with the conductor below and to fall to the ground. Automatic circuit-breaker operation cleared the section of line in trouble. The disturbance produced a registration on all but two of the instruments on the line conductors. In general, the surge recorded was of moderate value, but on *Y*-phase, tower 1692 of the H-8 line it reached a value of 7.7 times normal (880-kv.).

Surge Voltages Due to Switching Operations. Surge voltages recorded coincident with routine switching operations were 92 in number, were of highly damped figure characteristics, and reached a maximum value of 3.6 times normal (410 kv.). Switching on the two lines between Saginaw River and Flint invariably produced disturbance which recorded on the instruments, but switching on other parts of the 140-kv. system sometimes failed to produce registrations. Switching on equipment connected to the H-8 and K-11 lines through transformers produced no record on the instruments. Deenergizing of either the H-8 or K-11 lines resulted in voltage surges of higher magnitude than were produced by energizing the same line.

Surge Voltages from Unknown Causes. During the season, 49 surge voltages were recorded for which no cause could be assigned. These voltage disturbances were all oscillatory and, for the most part, very local in extent. They were of relatively small magnitude, the majority being less than 3.0 times normal (340 kv.), and the most severe 5.7 times normal (650 kv.). Surge voltages of highly damped, medium damped, and slightly damped characteristics were about equal in number.

It is thought that these surge voltages for which no cause could be assigned may have been produced by switching operations not listed in the load despatchers log, or by local lightning storm which were not noted by the operators.

Summary of Results

On the 140-kv. lines of the Consumers Power Company between Saginaw River and Flint in 1927:

1. Lightning produced voltage surges whose magnitudes were as high as 1100 kv.

2. During this particular investigation, all surge voltages of appreciable magnitude due to lightning recorded on the two-electrode instrument as oscillatory, with no preponderance of positive or negative polarity indicated. In a number of cases, the record of the surge from the lightning itself was undoubtedly considerably obscured by secondary oscillations from arcing grounds and circuit breaker operation.

3. The surge voltages due to lightning were characterized by three different figure types; highly damped, medium damped, and slightly damped.

4. Surge voltages characterized by medium damped figures showed very little change in value from station to station, and frequently correlated with arcing grounds and switch trip-outs.

5. Comparison of simultaneous registrations of highly damped and slightly damped surge voltages showed the reduction in voltage from station to station to be of the order of 50-kv. per mi. From insulator flashover, the attenuation appeared to be in the order of 100 kv. per mile.

6. The data indicated that the ground wire afforded some protection against lightning disturbances.

7. No definite relation was shown between conductor height and voltage recorded.

8. Surge voltages recorded coincident with switch trip-outs due to lightning frequently were of a magnitude less than 400 kv., though higher voltages undoubtedly existed on the line at points remote from recorder stations.

9. Lightning surges which produced no switch trip-outs were, as a rule, very limited in their extent although they were frequently of a very high value. (800-1100 kv.).

10. Under lightning conditions, voltages in excess of 35 kv. were built up between ground wire and ground at mid-span, without excessively high voltage on the line conductors. The voltage from ground wire to ground was always considerably less at the tower than at mid-span.

11. Normal switching operations produced surge voltages of low value which extended over considerable length of line.

12. Numerous surge voltages were recorded which could not be correlated with lightning storms or system switching. The magnitudes of such disturbances were relatively low, reaching values no higher than 5.7 times normal (650 kv.).

ACKNOWLEDGMENTS

The writers wish to acknowledge the assistance of members of the General Engineering Laboratory and Central Station Engineering Department of the General Electric Company, in conducting the investigation and in preparing this paper.

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2. *Directional Ground Relay Protection of High-Tension Isolated Neutral Systems*, by J.V. Breisky, J. R. North, and G. W. King, A. I. E. E. Trans., Vol. XLVI, 1927, p. 853.

3. *The Measurement of Surge Voltages on Transmission Lines Due to Lightning*, by E. S. Lee and C. M. Foust, A. I. E. E. Trans., Vol. XLVI, 1927, p. 339.

Discussion

For discussion of this paper see page 1147.

Surge Voltage Investigation on the 132-Kv. Transmission Lines of the American Gas and Electric Company

BY PHILIP SPORN[1]

Member, A. I. E. E.

Synopsis.—Data on the surge voltage investigation, carried out under the auspices of the Subcommittee on Lightning, on one of the 132-kv. lines of the American Gas and Electric Company during 1928, are presented. Most of the surges have been segregated as to cause, and plotted in summary form for more convenient use. The magnitude and character of recorded surges are discussed; and the conclusions drawn from data presented.

Information on voltage surges due to lightning, switching, trip-outs, and unknown causes are presented, as well as records of lightning arrester discharge currents, voltages across choke coils, and on the ground wire.

This paper is presented at this time to make available to the engineering profession some of the information obtained, before the report of the Subcommittee on Lightning is completed. As experimental work is still being done in the field during 1928, anything like a complete report cannot be made until next year.

I. Introduction

IN carrying out the work of the Subcommittee on Lightning of the Transmission and Distribution Committee of the A. I. E. E. with the author as Secretary, an extensive klydonograph layout was planned and placed in operation on the 132-kv. system of the American Gas and Electric Company during the lightning season of 1927. This work, started under the sponsorship of the Subcommittee on Lightning, was made possible by the co-operation of the General Electric Company, the Westinghouse Electric and Manufacturing Company, and the American Gas and Electric Company, and the subsidiaries of the latter, namely, the Ohio Power Company and the Appalachian Electric Power Company.

This paper presents some of the first data obtained from the investigation on one part of the system. It is planned to combine with all the 1927 work, data from other parts of the system, where the investigation was carried on, together with results secured from the continuation of tests during 1928, and present it later as a complete report by the Lightning Subcommittee.

II. System Investigated

In selecting a system on which to carry on this work during 1927, the Lightning Committee decided the 132-kv. Philo-Canton line of the American Gas and Electric Company was particularly well suited, as this line had experienced a great deal of lightning trouble when first placed in service.[2] It had been supplied, after careful study, with protective equipment designed to minimize lightning troubles; and it was situated in a section of the country where lightning storms were known to be unusually severe.

The Philo-Canton line is a 73-mi., double-circuit A. C. S. R. conductor line, with wires in vertical configuration, one circuit on each side of the tower. The line is equipped with ring and horn protection on all insulator strings, and with one ground wire at the peak of the tower. This line is in Ohio, parallel to, and about 50 mi. west of the Ohio River. The 123-kv. system is operated with solidly grounded neutral, the only ground on the Philo-Canton line being at the Philo end.

In carrying out the program, tests were made also on a 132-kv. lightning arrester at the Turner substation located in Charleston, West Virginia.

This paper covers only results obtained on the Philo-Canton line and on the lightning arrester at Turner substation.

III. Scope of Investigation

In planning the installation of instruments, locations were so chosen that it was expected valuable information would be obtained on the following:

1. Choke coil effectiveness.
2. Ground wire protection.
3. Polarity of lightning.
4. Transient voltages on the ground wire.
5. Functioning of lightning arresters.
6. Attenuation of voltage surges.
7. Voltage change at termination of ground wire.
8. Switching surges.
9. Action of tower ground resistance during insulator flashover.
10. Relative surge voltages on symmetrically placed parallel conductor.

The first instruments were placed in service May 10, 1927, and the major part of the installation completed about June 15. The investigation as a whole was concluded October 16, 1927, although some of the instruments at the stations, where they were accessible, were continued in operation throughout the winter of 1927-1928.

IV. Location of Instruments

The general location of klydonograph is shown in Fig. 1. The set-up included 37 G. E. double reverse electrode surge recorders and one Westinghouse four-electrode klydonograph. As connected, the instru-

1. American Gas and Electric Company, New York, N. Y.

2. *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines*, Sindeband and Sporn, A. I. E. E. TRANS., Vol. 45, 1926, p. 770.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

ments were capable of recording surges at 40 different points on the system. It was realized, of course, that while instruments were located with a definite object in view, they would obviously record any and all surges on the line and therefore, information other than that specifically planned for would be obtained.

In analyzing the layout, reference to Fig. 1 shows that stations Nos. 1 and 5, also 32 and 33, were located to determine the voltage change across choke coils. Ground wire protection data were expected from instruments 7 to 19, 21 to 23, 33, 34, and 35. From the instruments located at Stations 7 to 19, inclusive, it was expected that some information would be obtained on the attenuation of surges. Data on voltage characteristics at the termination of ground wire were expected at Stations 5, 41, 7, 29, and 32. A lightning arrester study was undertaken by instruments at Stations 4, 5, 24, 30, 31, and 38. At Station 42 an instrument was connected to the ground wire at the peak of the tower to measure the voltage on the ground wire. At Station 43, an instrument was connected from the base of the tower to an artificial ground system made from ground rods located at least 10 ft. from the base of the tower. This set-up was made to determine, if possible, any voltage change between the tower base and normal ground due to any drop through the tower ground resistance in case of flashover at this tower. Another interesting set-up is at Tower 172 including Stations 20, 21, 22, and 23. This set-up was made to compare the two different types of instruments used and their couplings to the line. Station 20 is a three-electrode Westinghouse klydonograph coupled to the line with pipe type potentiometers and Stations 21, 22, and 23 are equipped with G. E. surge-voltage recorders coupled to the line with insulator string potentiometers.

KLY STA N°	MAKE OF INSTR	LOCATION	KLYDONOGRAPH CONNECTIONS
1	G.E.	Canton	Top phase - bus side of choke coil
2	G.E.	"	Middle " " " " " "
3	G.E.	"	Bottom " " " " " "
4	G.E.	L.A. Canton	Light. Arrest. ground - west circuit
5	G.E.	Canton	Top phase - line side of choke coil
6	G.E.	L.A. Canton	Light. Arrest ground - east circuit
7	G.E.	Tower 296	Top phase
8	G.E.	" "	Middle phase
9	G.E.	" "	Bottom phase
10	G.E.	" 204	Top phase
11	G.E.	" "	Middle phase
12	G.E.	" "	Bottom phase
13	G.E.	" 200	Top phase - West circuit
14	G.E.	" "	Top phase
15	G.E.	" "	Middle phase
16	G.E.	" "	Bottom phase
17	G.E.	" 198	Top phase
18	G.E.	" "	Middle phase
19	G.E.	" "	Bottom phase
20	Westh	" 172	Top - Middle - Bottom phase
21	G.E.	" "	Top phase
22	G.E.	" "	Middle phase
23	G.E.	" "	Bottom phase
24	G.E.	L.A. New't's	Light. Arrest. ground - Bus
25			
26	G.E.	Tower 134	Top phase - West circuit
27	G.E.	" "	Top phase - East circuit
28	G.E.	" 3	Top phase - West circuit
29	G.E.	" 3	Top phase - East circuit
30	G.E.	L.A. Philo	Light. Arrest ground - West circuit
31	G.E.	" "	" " " East circuit
32	G.E.	Philo	Top phase - line side of choke coil
33	G.E.	"	" " - bus " " " "
34	G.E.	"	Middle " - line " " " "
35	G.E.	"	Bottom " - " " " " "
36			
37			
38	G.E.	L.A. Turner	Light. Arrest. ground
39			
40			
41	G.E.	Tower 297	Top Phase - East circuit
42	G.E.	" "	Ground wire on Tower
43	G.E.	" "	Base of Tower 297 to Ground

KLYDONOGRAPH STATION SPACING		
FROM	TO	DISTANCE
Canton Bus	Tower 296	1590 ft.
Tower 296	" 204	22.85 mi.
" 204	" 200	4224 ft.
" 200	" 198	9728 ft.
" 198	" 172	7.26 mi.
" 172	New't's Bus	7.58 mi
New't's Bus	Tower 134	5174 ft.
Tower 134	" 3	31.56 mi.
" 3	Philo Bus	3490 ft.
Canton Bus	Tower 297	300 ft

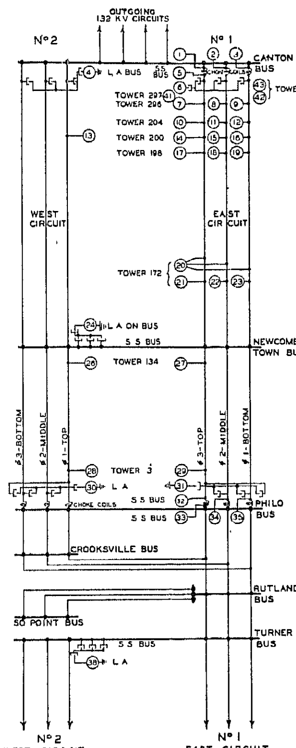


FIG. 1—KLYDONOGRAPH LAYOUT—132-KV. SYSTEM 1927 TESTS

Two typical set-ups of the instruments in the field at Stations 20, 21, 22, and 23 are shown in Figs. 7 and 8. Figs. 7 and 8 show the tap leads extending from the line to the klydonograph stations located at the base of the tower, both pipe type and insulator string potentiometers with klydonographs appearing clearly in the foreground.

The insulator string potentiometer connections at Stations 1, 2, 3, and 5 are shown in Fig. 9. The klydonograph is shown tapped across the lower insulator of the entire string. In the first part of the test the instrument was tapped across the two lower units, but this connection was later changed so as to tap one unit, thereby increasing the potentiometer ratio.

V. POTENTIOMETER COUPLING TO 132-KV. CIRCUITS

The klydonograph and surge voltage recorder, the action of which is well known, has been described previously.[3] Since these instruments are suitable for connecting to a circuit, the crest voltage of which under surge conditions ranges from 1500 to 30,000 volts,[4]

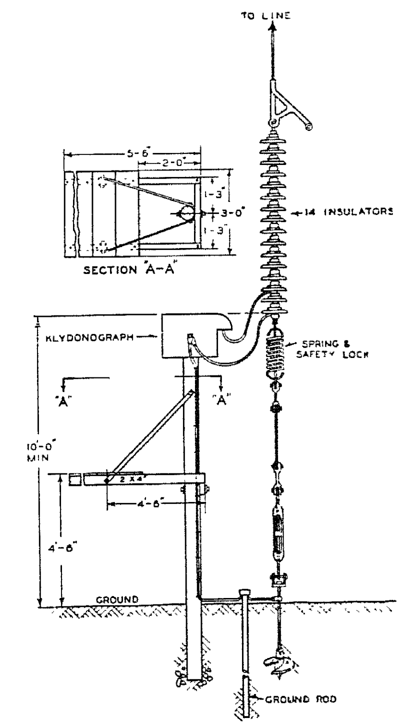


FIG. 2

3. *The Klydonograph and Its Application to Surge Investigation*, Cox and Legg, A. I. E. E. TRANS., Vol. 44, 1925, p. 857.

The Measurement of Surge Voltages on Transmission Lines due to Lightning, Lee and Foust, A. I. E. E. TRANS., Vol. 46, 1927, p. 339.

4. The klydonograph will not record crest voltages below 1500, and flashes over around 30,000.

the instrument must be provided with suitable reduction equipment to connect to high-voltage circuits of the order of 132,000 volts (108,000 volts crest to ground). In these tests two types of potentiometers were used to reduce the normal line voltage to a voltage suitable for the instrument. One type, the insulator string potentiometer, is shown in Fig. 2, and consists essentially of 14 line insulators with the instrument tapped across the lower insulators on the ground end of the string. This type of potentiometer connected to the high voltage side of the circuit, was used with all G. E. surge recorders. The other type potentiometer shown in Fig. 3,

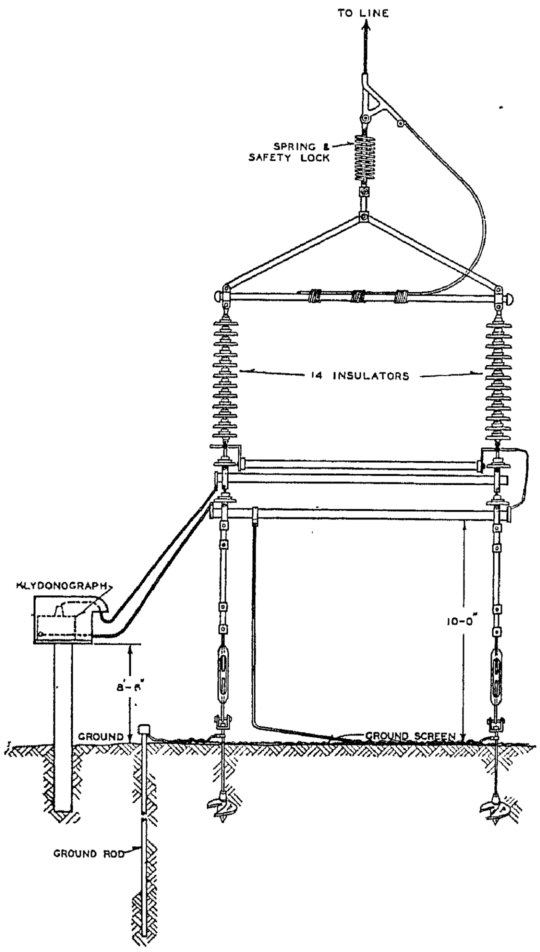


Fig. 3

was used on the Westinghouse klydonograph. This potentiometer consists essentially of four 3-in. pipes approximately ten feet long assembled with two strings of line type insulators. With the insulator string potentiometer a ratio of approximately 52/1 was secured when tapping the bottom insulator and 38/1 when tapping the bottom two insulators. The ratio used with the pipe type potentiometer was approximately 65/1. There are two main differences in these two types of potentiometers. First, with the insulator type the dielectric field is principally in porcelain, while with the pipe type it is mainly in the air. Second, the klydonograph is tapped across a part of the insulator string leakage path with the insulator string type potentiometer, but this is not the case with the pipe type of potentiometer.

VI. Character of Surges

The general types of Lichtenberg figures obtained on all records are shown in Figs. 4, 5, and 6. In Fig. 4, surge 1 is a typical lightning figure, which is described as highly damped, and it will be noted from the figure

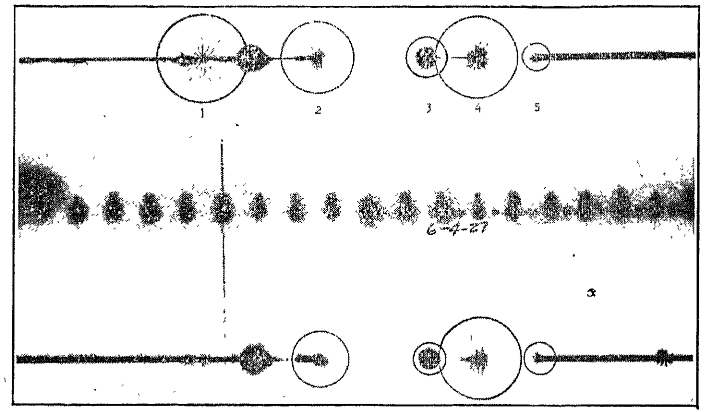


Fig. 4—Surge-Voltage Recorder Field Record—Ohio Power Co.

1 typical lightning (HD) figure
2 & 4 (HD) figures, line deenergized
3 & 5 (HD) figures, line energized

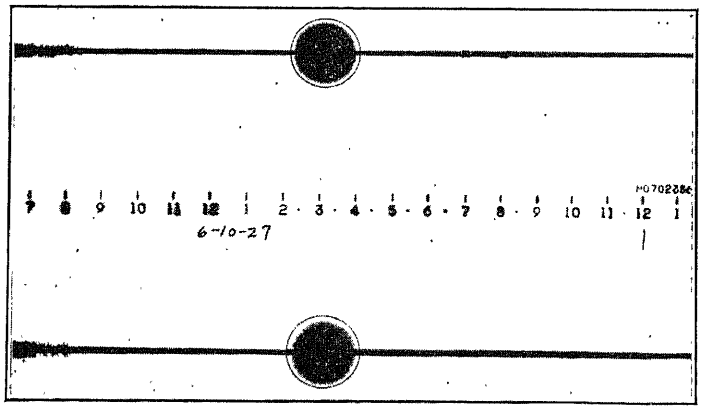


Fig. 5—Surge-Voltage Recorder Field Record—Ohio Power Co.

Typical (SD) figure

that there is a large positive and a very small corresponding negative just observable above the normal voltage band (the large figure may be positive or negative, depending upon which electrode originally recorded it). Surges 2 and 4 are typical switching surges of a highly damped nature and indicate a rather high voltage, but with only a few reversals of high magnitude. This is clearly shown by the lack of density in the figures. Surges 3 and 5 are also switching

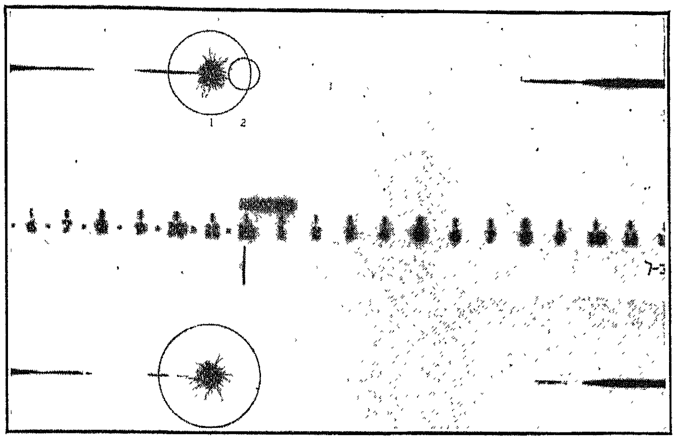


FIG. 6—SURGE-VOLTAGE RECORDER FIELD RECORD—OHIO POWER CO.

Special switching operation. 1—Line deenergized at Canton 2—Line energized at Canton

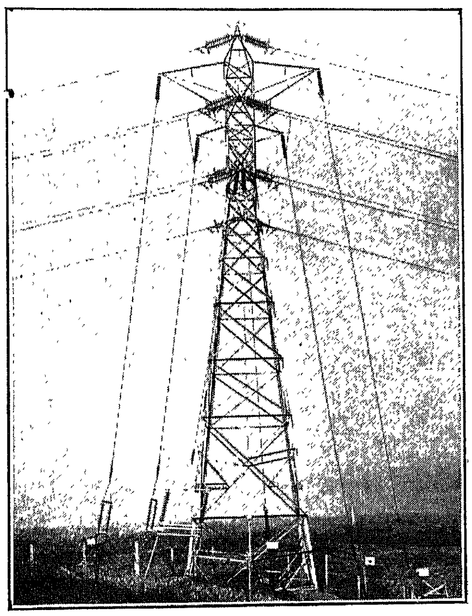
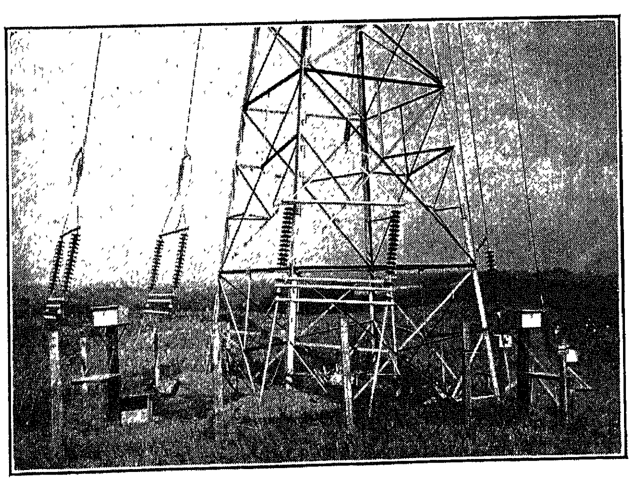


FIG. 7—FIELD INSTALLATION OF SURGE RECORDERS

Tower 172 showing line coupling
Philo-Canton 132-kv. line



8—FIELD INSTALLATION OF SURGE RECORDERS

Tower 172 showing line coupling
Philo-Canton 132-kv. line

surges of a lower magnitude with surge No. 3 showing a tendency for a sustained voltage considerably in excess of normal line voltage. A typical slightly damped figure is shown in Fig. 5. In general, this type of picture indicates an oscillatory voltage sustained for a relatively long period of time. Its reproduction in the laboratory has been approximated by normal frequency voltage for a period in the order of a minute. Although it has never been perfectly reproduced in the laboratory, such attempts as have been made seem to indicate it requires an oscillating voltage and also an appreciable element of time.

A number of this type of surge was obtained during the test period, but as their presence could not be explained, and since, as described later, they appeared to be a function of the potentiometer used, they have

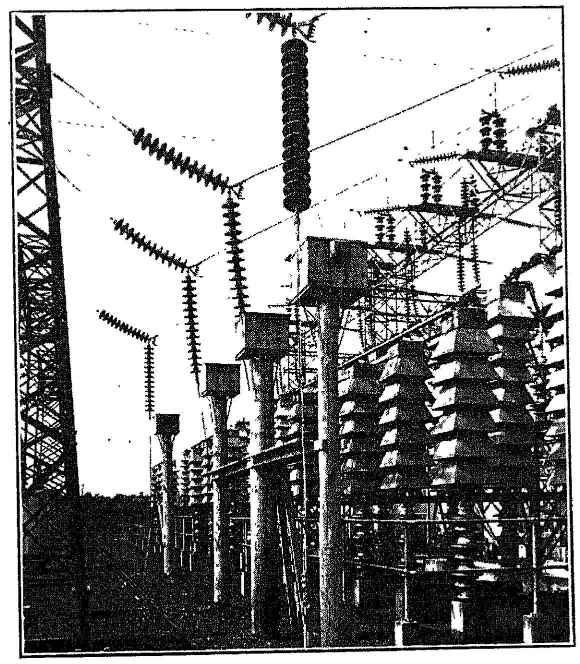


FIG. 9—SURGE RECORDER INSTALLATION

Canton 132-kv. station
Stations 1, 2, 3, and 5

not been used in presenting data in this paper, except to indicate that they have existed.

Other typical switching surges are shown in Fig. 6, surge No. 1 being a line deenergizing surge and surge No. 2 being a line energizing surge both recorded at the Canton end of the line.

VII. DATA OBTAINED AND ANALYSIS

During the period of instrument operation up to October 16, 1927, approximately 3600 Lichtenberg figures, resulting from 550 surges, were obtained on the Philo-Canton section of the system. These surges were classified and regrouped so that a detailed study might be made of any particular type of surge. On the Phil-Canton line these surges have been classified according to cause, as follows:

TABLE I

	Total	Excluding slightly damped
Unknown origin	295	272
Outside switching	29	26
Pure switching surges	101	101
Lightning surges	166	96
Combined lightning and switching	6	4
Lightning arrester discharges	40	40
Ground wire surges	68	68

Outside and Pure Switching Surges. For more convenient study, the surge data have been assembled into summary curves, two of which are shown in Fig. 10. The lower curve applies to outside switching surges and shows that of 26 surges the maximum was 1.8 times normal and that 50 per cent of them were over 1.4 times normal. Outside switching surges are classified as surges originating from switching on parts of the system other than where instruments are located. In some cases surges were caused by switching on the secondary

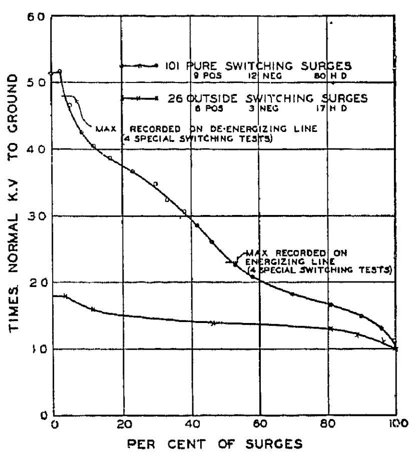


FIG. 10

side of the transformers connected to the 132-kv. line. This type of surge has also been included in this curve.

The upper curve of this Fig. 10 shows the results of 101 pure switching surges with maximum recording value of 5.2 times normal. These surges have been segregated as to nature, showing 9 positive, 12 negative, and 80 highly damped. Two points of the curve have been marked, indicating the maximum recorded voltage on energizing; also on deenergizing the line. These two points were the results obtained on four separate switching tests of the Philo-Canton line, in which surges caused by energizing and deenergizing the line as well as switching load at Newcomerstown (the approximate half way point of the line) were separated by one hour intervals. In the earlier part of the tests it was found that lightning and switching surges occurring at the same time caused some confusion due to the absolute impossibility of separating the switching part of the surge from the lightning part. It was therefore decided to separate the switching surges by one hour intervals in a prearranged test and in this way study the effects of switching load, deenergizing the line, and energizing the line. Results show that the maximum recorded surge occurred on deenergizing the line and was 4.8 times normal. On energizing the line the maximum surge was 2.3 times normal.

To show the effect of the switching voltage through-

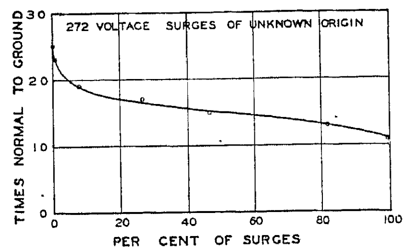


FIG. 11

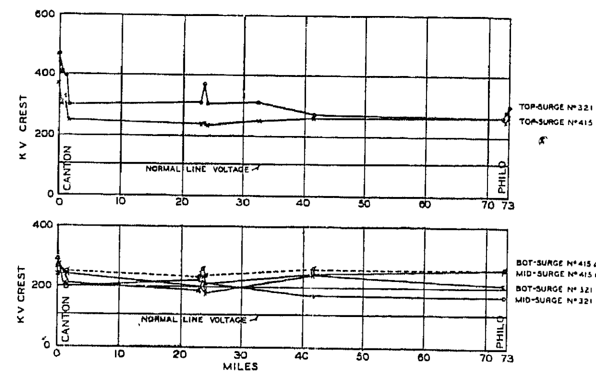


FIG. 12—PURE LINE SWITCHING SURGES

May 10 to Oct. 16, 1927
Philo-Canton 132-kv. line
Deenergized at Philo station

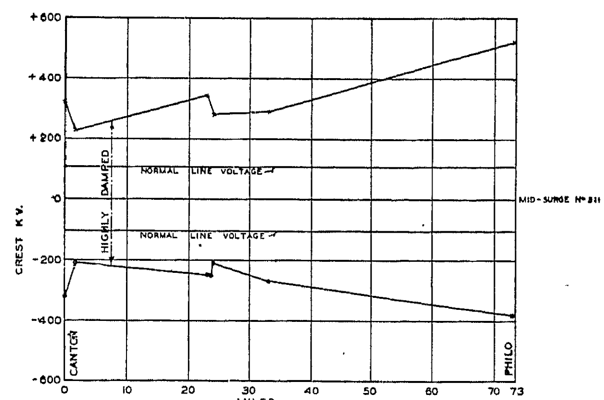


FIG. 13—PURE LINE SWITCHING SURGES

Philo-Canton 132-kv. line on July 30, 1927—11.00 p. m
Deenergized at Canton station

out the entire length of the line, the records obtained on three of these switching surges are shown in Figs. 12 and 13. The point of interest is that the switching surge travels with apparently little change in the voltage throughout the entire length of the line. The irregularities in the curves are probably within the limits of accuracy in the instruments and the distinct tendency of higher voltages at either end of the line due to reflection will be noted.

Surges of Unknown Origin. Surges of unknown origin on the Philo-canton line are shown graphically in Fig. 11. While there were 272 surges for which no cause could be found, it will be noted that these never exceeded 2.5 times normal and only five per cent of them exceeded two times normal. This type of surge can be dismissed as being unimportant in magnitude, although constituting a comparatively large number of voltage changes on the line.

Lightning Surges. The 96 lightning surges on the Philo-Canton line are summarized in Fig. 14. The maximum surge indicated is 4.4 times normal and 50 per cent of the surges are above one and one-half times normal. These surges have been segregated as to nature predominating in each surge, as follows: 25 negative, 42 positive, and 29 highly damped.

Lightning and Lightning Surges. The four lightning surges on the line causing line trip-outs, gave maximum voltages of 5.0 and 3.7 times normal to ground. These were slightly damped surges, and it is believed may have been caused by the switching surge following the lightning voltage flashover. The other two surges recorded a maximum of 5.4 and 6.2 times normal, but both being S. D. figures, the results were not seriously considered. Since lightning voltages over double the values recorded above are necessary to cause insulator flashover, it is clear, even with a fairly large number of instruments on the line, there is no certainty that anything like the maximum voltage on the line will be recorded. As sections of line in the order of 25 mi. existed where no surge recorder was located, this shows that the lightning voltages did not travel with destructive values any

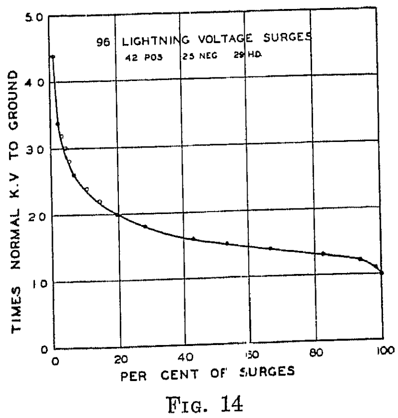


FIG. 14

great distance. This characteristic of the lightning surge is distinctly different from the switching surge.

Voltage Drop Through Choke Coils. The attempt to measure the voltage drop through choke coils was rather ineffective on account of the existence of S. D. figures in the records. However, of 10 lightning surges (no S. D. figures included) the bus side of the choke coil was the higher on four surges, averaging nine per cent higher than the line side and on six surges the line side of the choke coil was higher, averaging 25½ per cent higher voltage than on the bus side. It can only be said that a tendency exists, as indicated, for the choke coil to reduce the lightning voltage originating on the line in the order of 25 per cent, but it is not felt that sufficient data on this subject have been obtained to prove finally the effectiveness of the choke coil.

Lightning Arrester Data. The data on all six lightning arresters are summarized in Fig. 15. The only

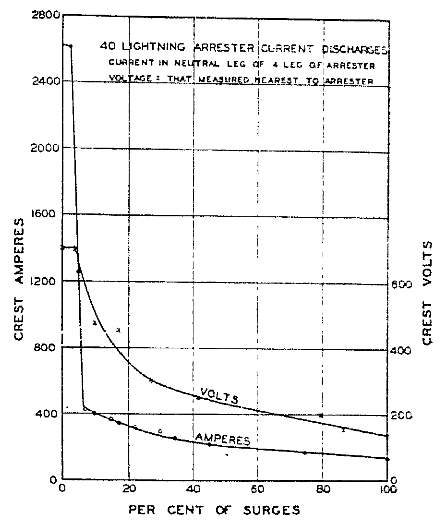


FIG. 15

record of current discharge in the arresters was obtained at Newcomerstown and Turner substations. No records were obtained at Philo or Canton on lightning arresters due apparently to the arrester not discharging, although the instrument was set up to record a current as low as about 150 amperes in the neutral leg. In Fig. 15 it should be noted that the current and voltage are not simultaneous readings. Forty lightning arrester discharges were recorded; 21 were positive, 11 were negative, and 8 were highly damped. Of the lightning discharges 12 were positive, eight negative, and four highly damped. Of the switching discharges one was positive and one negative. Of the discharges due to unknown causes nine were positive, two negative, and two highly damped. One discharge due to an arcing ground registered minus 360 and plus 410 amperes, being of a highly damped nature. An attempt to plot a curve of current against voltage recorded resulted in a shotgun curve of little value. It is felt that considerably more work will have to be done in securing lightning arrester data before any definite conclusion is arrived at.

Lightning Surges on Parallel Circuits. The data secured at instruments located on the top wires of the two Philo-Canton lines (eliminating S. D. figures) gave nine surges including four positive, two negative, and three highly damped. The ratio of the two lines at any point varied from 0.80 to 1.25, averaging 1.03. The minimum voltages occurring during these surges were in the order of 120 kv. to 140 kv. minimum to a maximum of 340 to 400 kv. The data here, again, are too meager to prove definitely that the induced voltages

on the two wires are equal; but this tendency is indicated.

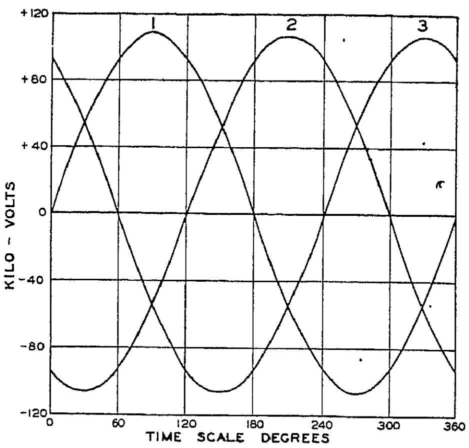
Tower Base Voltages. At Station 43 where an instrument was located to determine the voltage between the tower base and ground, no records were obtained during the season. It should also be noted that at this tower there were no flashovers of the line.

Comparison of Potentiometer Couplings at Tower 172. This location of instruments was made to give a comparison of instruments and of potentiometer couplings. Some 300 records were obtained on the instruments located at this station from which certain and definite data were obtained. It was shown that the two types of instruments were equally effective in recording surges, but that there was a distinctly troublesome difference between the pipe type and insulator string type potentiometer. In practically every case the instruments recorded surges of unidirectional or highly damped surges equally well on both potentiometers, but when there were surges on the line, apparently due to lightning, the instrument connected to the pipe type potentiometer practically always recorded unidirectional surges. At this time, however, the instrument connected to the insulator string potentiometer would frequently record surges of a slightly damped nature. That this occurrence was due to the potentiometer alone was definitely proved by coupling two separate instruments to the same point on the line, one through a pipe type and the other through an insulator string type potentiometer. Slightly damped surges, six and one-half times normal and above, were recorded at this station through the insulator string potentiometer which failed to indicate at all through the pipe type coupling. Slightly damped figures as low as 1.8 times normal have been recorded through the insulator string potentiometer which failed to give any record at all through the pipe type coupling.

A study of results secured at this tower led to the conclusion that all of the so-called slightly damped surges recorded in the investigation should be excluded from analysis and consideration, in a study of the data; and this practise has been followed in this report.

Study made subsequently in the laboratory confirmed the impression that the S. D. figures are brought about in some way by a condition in the circuit of the insulator string type potentiometer, and that while a surge occurrence on the line may set off the circuit that finally produces the S. D. figures, that no potential of the order generally indicated by the S. D. figures actually exists on the line itself. All the laboratory work failed to disclose a means whereby an S. D. figure could be actually reproduced. As a consequence, the conclusion was reached to disregard the S. D. figures obtained on the insulator string potentiometer on past work, and in future work to adhere either to the pipe type potentiometer or to a modification of the string potentiometer that would definitely preclude the possibility of the S. D. figure recurring. It appears that if the circuit is so arranged that the instrument itself is not shunted across the 60-cycle leakage path, the S. D. figure will not show up; and work is being done in several directions to effect this change in the potentiometer coupling. From this standpoint it is felt that the layout at Station 172 was a particularly fortunate one, and contributed considerably to the study of lightning phenomena by means of the klydonograph. It has resulted in definitely disclosing a weakness in one type of potentiometer arrangement and has eliminated the possibility of misleading conclusions as a result of faulty data.

Effect of Normal Line Potential on Recorded Voltages. The surge recorder shows the maximum crest voltage at its terminals, and by the use of the potentiometer ratio,



CREST 60 KV. OF LINE WIRES TO GROUND.													
DEGREES	0	30	60	90	120	150	180	210	240	270	300	330	360
PHASE-1	0	+54	+93	+108	+93	+54	0	-54	-93	-108	-93	-54	0
" 2	-93	-108	-93	-54	0	+54	+93	+108	+93	+54	0	-54	-93
" 3	+93	+54	0	-54	-93	-108	-93	-54	0	+54	+93	+108	+93

FIG. 16—INSTANTANEOUS VOLTAGE OF 132-KV., THREE-PHASE LINE

the crest voltage on the line, when potentiometer coupled to the circuit under investigation. It is, therefore, clear that a recorded surge must be the instantaneous sum of the surge voltage and the line voltage. In Fig. 16 are shown the instantaneous voltages of the three line wires of a 132-kv. circuit during one complete cycle.

Now assume a voltage surge of 300 kv. positive on all three line wires, and further, that this surge occurs at 210 deg. on the time scale. Due to normal line voltage No. 2 phase is 108 kv. above ground, and No. 1 and No. 3 phases 54 kv. below ground. Surge recorders at this location would indicate the sum of normal plus surge voltage; and conditions in Table II would obtain.

While 18 per cent error in surge recorder instruments, including line coupling in their present stage of develop-

TABLE II

	Phase 1	Phase 2	Phase 3
Surge voltage (kv.)	300	300	300
Line voltage (kv.)	100	−54	−54
Recorded voltage (kv.)	400	246	246
Per cent error	33	18	18

ment, is perfectly reasonable, and 33 per cent may be slightly excessive, let us examine the ratio of recorded to actual voltages on phases 1 and 2. This ratio is 1.63 for the recorded voltage and 1.00 for the actual voltage, giving an error of 63 per cent, which is distinctly excessive if the data are to be used in studying surge voltage attenuation, effect of the ground wire, voltages on lightning arresters and the like.

It should be pointed out, however, that the effect of normal line voltage on surges decreases with increase of the surge magnitude. An error of 63 per cent with a 300-kv. superimposed surge becomes only 18 per cent for a 900-kv. surge. With surges of low magnitude the error becomes greater; and in some cases an erroneous conclusion may be reached unless the influence of normal line voltage is considered.

While the above feature is decidedly fundamental, it is felt that its importance in analyzing data should be emphasized at this time to forestall any wrong conclusions being drawn from data, particularly where surges of the lower magnitudes are involved.

VIII. Conclusions

1. The choke coils reduced the recorded lightning voltage in the order of 25 per cent, although tests on this feature are not extensive enough to prove this statement conclusively. Reflections at the choke coil may also have had a decided effect in altering the incoming voltage wave, so that this 25 per cent may not have been an actual reduction of the initial wave.

2. The protective value of the ground wire could not be proved conclusively from the data, due largely to the presence of S. D. figures in the records. It is planned to continue this investigation the coming year.

3. The record on instruments at the time of line trip-outs due to lightning (maximum 5.0 times normal voltage is found) indicates that the voltages higher than recorded must have existed on the line for flashover to have occurred. This brings up the point that surge recorders must be placed in generous numbers on a line to study line performance thoroughly. A further tendency is indicated from these data, that is, that lightning voltages do not travel a great distance; otherwise there would have been recorded high voltages on some of the surge recorders.

4. The polarity of lightning surges indicated a preponderance of positive impulses. Of 96 surges 42 were positive, 25 negative, and 29 highly damped.

5. Transient voltages on the ground wire at the tower were recorded as high as 8200 volts negative during a lightning storm, and in all cases were of the order of 3000 to 4000 volts. These surges were recorded at times of lightning storms and switching; in some cases no cause could be found. This relatively low voltage on the ground wire compared with the higher voltage on the line is positive evidence of the effectiveness of the ground wire in reducing the impulse voltages on the line itself.

6. Lightning arrester discharges in all cases were of the general order of 200 to 400 amperes, although two cases were recorded as high as 1260 and 2620 amperes. Measured currents were in all cases the sum of the currents in all three legs of the arrester. The highest recorded current was negative; the 1260 ampere value was highly damped, being initially negative.

7. Attenuation of lightning surge voltages failed to give any conclusive results largely on account of the presence of S. D. figures.

8. The attempt to determine voltage changes at the termination of the ground wire was not very successful due largely to insufficient reliable data and the proximity of the test point to the substation where the numerous changes in surge impedance introduced the question of reflected waves.

9. Switching surges have been recorded as high as 5.2 times normal, which seems to be in general agreement with previous results. Over 50 per cent of the switching surges were of the order of two and one-half times normal to ground or higher. By isolating switching surges in four special tests, it was shown that the surge voltage on deenergizing the line was approximately twice as great as on energizing the line. Switching surges are mostly of a highly damped nature, as shown by the data.

10. No voltage was recorded between the base of a tower and ground, during the tests, although the voltage at the peak of the tower to which the ground wire was attached indicated surge voltages up to 8200 volts.

11. The relative lightning voltage on parallel conductors is shown to be equal, although the data are too limited to prove this point definitely.

12. It was shown that the two types of surge recorders are equally reliable from the point of view of measuring surges; but it was also shown that the type of coupling employed to connect the instruments to the line must be carefully studied and selected or erroneous conclusions may result. This point is clearly shown from the experience at Tower 172, Stations 20, 21, 22, and 23.

13. This investigation, it is believed, has resulted in some new information, some confirmatory and some negative. All this information is valuable, although a great deal more data must be obtained to properly solve the lightning problem. With this data, together with the data it is hoped to get during the year 1928 lightning season, it is believed some further light will be thrown on the lightning voltage situation.

Acknowledgment is due to the various men in the organization of the General Electric Company, the Westinghouse Electric Manufacturing Company, the American Gas and Electric Company, the Ohio Power Company, and Appalachian Electric Power Company, who participated and helped in the work of this investigation.

Discussion

For discussion of this paper see page 1147.

Surge Voltage Investigation on 220-Kv. System of Pennsylvania Power and Light Company

BY NICOLAS N. SMELOFF[1]

Associate, A. I. E. E.

***Synopsis.**—This paper presents the history of the operating experience and surge-voltage recorder data for the years 1926 and 1927, on the first 220-kv. line in the East.*

The system of the Pennsylvania Power & Light Company is described. Lightning weather data, design characteristics of the 220-kv. line involved, and details of connection and installation of surge-voltage recorders are given.

The study shows the magnitude of surge voltages encountered, method of classification, effect of our overhead ground wires, etc., and points out the necessity for comprehensive lightning research, which will permit a systematic solution of transmission problems.

* * * * *

General

THE system of the Pennsylvania Power & Light Company is located in the northeastern part of Pennsylvania. It traverses several mountain ranges, which attain a maximum elevation of 2100 ft. In the anthracite coal fields and in the northern part of the system the terrain is particularly rugged, rocky, and exposed to storms.

Coal mining, cement, metallurgical, slate, textile, furniture, shoe, and other miscellaneous industries provide a field for a desirable, important, and diversified load. In addition to the above, a number of large communities depends entirely upon this system for electrical power. The natural growth of the system and favorable economic conditions permit the establishment of interconnections with practically all neighboring systems.

Power is generated in eight major steam stations. With one exception these stations use small sizes of anthracite—either pulverized or on stokers. In addition, one major hydroelectric station of 40,000-kw. capacity at Wallenpaupack furnishes power during peak load periods. This hydroelectric development, because of its design and method of operation, provides on short notice (90 to 120 sec.) a capacity which assists materially in the economical operation of the steam stations.

The present major network and primary distribution is operated at 66,000 volts. Over 50 per cent of this 66-kv. network is on wood pole lines. Numerous step-down transformer stations are connected directly to the main lines, thus affording readily accessible power to large, as well as comparatively small consumers at the system primary voltage.

This 66-kv. system, at present, is connected at Siegfried with the hydroelectric station at Wallenpaupack by means of a 220-kv. transmission line, which was placed in operation in 1926. Although it was the first line operating at this potential in the East, of far more importance is the fact that it was the first 220-kv. line in lightning infested territory, and for this reason it afforded the first substantial experience with an opportunity for study of the effects of lightning on a line and equipment insulated for 220-kv. operation.

During 1928, additional lines at 220-kv. were placed in operation establishing an interconnection between the systems of the Philadelphia Electric Company and the Pennsylvania Power & Light Company, and consequently tying together the two hydroelectric stations, Conowingo and Wallenpaupack. This connection is shown on the map of Fig. 1. Later these lines will be a part of an extensive 220-kv. network and interconnection between large stations of several systems.

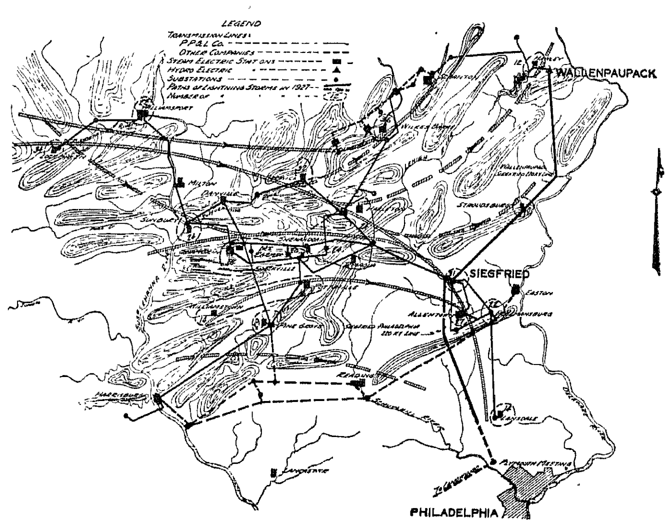


FIG. 1—MAP OF PENNSYLVANIA POWER & LIGHT CO. SYSTEM

Showing major transmission lines, power plants, substations, and the path and number of lightning storms for the season of 1927

Lightning Weather Data

Lightning weather observations were made by the operating organization at numerous company substations. The data thus obtained were analyzed in conjunction with the U. S. Weather Bureau records.

The map (Fig. 1) indicates the principal mountain ranges and valleys and the paths of lightning storms during 1927. The solid lines denote the main general paths of the storms, while the broken lines indicate divergencies and show how storms break up and follow

1. Assistant to General Superintendent, Pennsylvania Power & Light Co., Allentown, Pa.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

different routes. In general, the storms seem to follow the mountain ranges rather closely, breaking through at points where streams have formed definite gaps. The general cyclonic storms moving eastward over the territory, extend from the northern to the southern edges of the system and during the course of their travel are reported from practically all stations. Of approximately 60 storms occurring during the 1927 season, 25 were of this wide-spread type, 26 were of a generally local type, following only one of the various paths indicated, while the remainder were entirely local, being reported from only one or two adjacent stations.

The duration of the storms is variable. The purely local storm may last from fifteen minutes to three hours, depending on conditions at the time it occurs. The general type of storm may be in evidence for a period ranging from two to seven hours before it has entirely disappeared from all parts of the system.

The map (Fig. 1) also shows, for the year 1927, the number of lightning storms reported from various locations. These data are not indicative of storm severity or duration and may or may not represent an average year. From this information it may be seen that the system under discussion is subjected to lightning storms in excess of the average over the country.[2] The records show that during 1927, 35 of the total of 59 storms observed caused line trip-outs, for the year 1926, 40, and for 1925, 51 storms caused trip-outs and were recorded. No complete record was kept of storms which did not affect operation during these earlier years.

Object of Surge Voltage Study

The importance of successful operation of large transmission systems cannot be overemphasized, and the minimizing of the effects of voltage disturbances caused by flashovers due to lightning is of importance. In eastern territory lightning is a major and uncontrollable source of trouble and is the most complicated and least known phenomenon. As a result, the power industry has before it the big problem of lightning research—what lightning is, how to handle it, and how to apply this knowledge in obtaining better line performance.

The comprehensive collection of operating data, supported by data from surge voltage recorders, laboratory research, study, and correlation of facts will undoubtedly permit, within a few years, a systematic solution of transmission problems.

The surge voltage recorder is a big and important tool in lightning research in the field. It permits, with certain limitations, the study of lightning potentials, wave shape of impulses encountered on transmission lines, attenuation, effect of overhead ground wires, etc. It throws some light, also, on the little known phenomenon of the relation of lightning and power arcs.

Of course, the value of the data resulting from the study covered by this paper, obtained during a short period of time, should not be overestimated, and deductions so drawn cannot be considered as indisputable facts. On the other hand, the possibility of obtaining a mass of rather conflicting data at the outset should not discourage further studies, as its dependability will increase with the length of period observed, *i. e.*, with the number of lightning seasons.

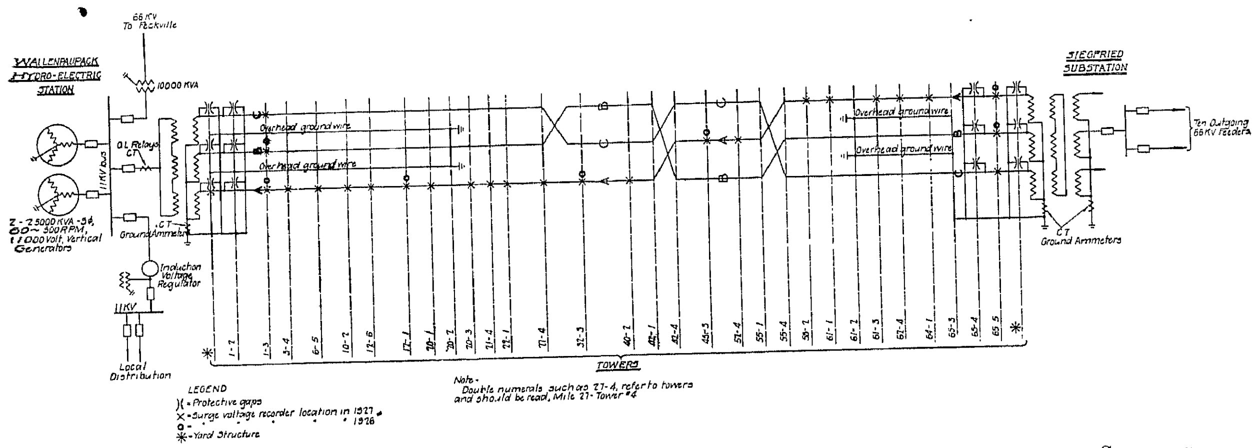


FIG. 2—One Line Diagram of Wallenpaupack-Siegfried 220-Kv. Line and Terminal Stations

Showing locations of surge-voltage recorders, transpositions, protective gaps, and overhead ground wires

The Wallenpaupack-Siegfried Line

The terrain crossed by the Wallenpaupack-Siegfried Line is mountainous, quite rugged, rocky, and timbered at its northern end where a maximum altitude of 2100 ft. is attained. Rolling farming country prevails at the southern end. When excavations for the tower footings were made, it was found that over a large portion of the line, the material removed consisted of broken or loose rock which was very difficult to drill or bore. The ground and tower footing resistance averages 50 ohms, with a maximum of 325 ohms on the mountain tops.

2. Overhead System Reference Book, N. E. L. A., p. 479, Table 122.

Table I gives the general characteristics of the line,[3] and Fig. 2 indicates the terminal connections. Table II contains pertinent information about the terminal apparatus, and Fig. 2 is the one line diagram. Fig. 3 shows the standard "A" type of tower. Fig. 4 shows the suspension insulator assembly with ring and horns.

During the summer of 1927 (May-July) two overhead ground wires were installed for the approximate distances of 20 miles at the Wallenpaupack (northern) end of the line and of five miles at the Siegfried (southern) end.

Surge Voltage Recorders

The surge voltage recorder study was made co-operatively by the General Electric Company and the Pennsylvania Power & Light Company. The former furnished a number of surge voltage recorders which the latter installed and serviced throughout the seasons. The data from the instruments were analyzed, and were correlated with the system operator's log and weather reports.

TABLE I

GENERAL CHARACTERISTICS OF THE WALLENPAUPACK-SIEGFRIED LINE

Frequency	60 cycles
Voltage—	
Between phases	220,000 volts
Phase to ground	127,000 volts
Normal crest volts to ground	180,000 volts
60-cycle flashover (dry)	600,000 volts
Line insulation flashover at lightning voltages, approximately	1,800,000 volts
*Protective gaps at stations—flashover at lightning voltages	1,300,000 volts
Circuits	1
Right-of-way	100 ft. cleared and danger timber cut
Length	65 mi.
Type of construction	Steel tower
Configuration of conductors	22.5 ft. flat
Height of conductors at tower	65.7 ft.
Height of ground wires at tower	75.5 ft.
Average span	1,100 ft.
Maximum span	2,400 ft.
Conductor	795,000 cm. A. C. S. R.
*Ground wire—two	184,000 cm. A. C. S. R.
Insulators—	
Locke No. 7500 high strength unit:	
Suspension assembly	14 units
Tension assembly	16 units
Arc protection and grading	Rings at line end, horns at ground end.
Distance from grading ring to horn of suspension assembly	5 ft. 11¼ in.
Transpositions	See Fig. 2
Relays:	
Wallenpaupack	Overcurrent and ground
Siegfried	Overcurrent and reverse power

*Installed in 1927.

The recorder used was the General Electric two-electrode instrument,[4] which makes possible the measurements of transients by positive Lichtenberg figures.

3. "Wallenpaupack Hydro Electric Development," A. E. Silver and A. C. Clogher, *Electrical World*, July 24, 1926.

4. *Measurements of Surge Voltages on Transmission Lines Due to Lightning*, by E. S. Lee and C. M. Foust, A. I. E. E. Trans., Vol. XLVI, 1927, p. 339.

TABLE II

GENERAL CHARACTERISTICS OF SUBSTATION EQUIPMENT

Transformers:	
At Siegfried	
Four single-phase units, bank capacity	86,600 kv-a.
High voltage	127,000/220,000 Y – 114,000/198,000 Y
Low voltage	38,100/ 66,000 Y –
Tertiary	10,750 Delta
Manufacturer	General Electric Co.
At Wallenpaupack:	
Four single-phase units, bank capacity	50,000 kv-a.
High voltage	134,000/231,000 Y – 121,000/209,000 Y
Low voltage	11,000 Delta
Manufacturer	General Electric Co.
220-Kv. Oil Circuit Breakers:	
Wallenpaupack	None
Siegfried	None*
Lightning Arresters:	
Wallenpaupack	None
Siegfried	None

Note. All switching of the energized line is done from 11 kv. and 66 kv. side of transformers at Wallenpaupack and Siegfried respectively. Neutral dead grounded at each transformer station.

*Three 220-kv. oil circuit breakers placed in service in 1928 with the advent of the Siegfried-Philadelphia 220-kv. line.

The instrument was connected to the line through a capacitance potentiometer consisting of a string of 20 Locke No. 7500 disk insulators, one end of which was connected to the line and the other to ground. The instrument potential was obtained by a connection to the cap of either the second, third, or fourth insulator from the grounded end of the string depending upon potentiometer ratio desired (see Tables III and IV).

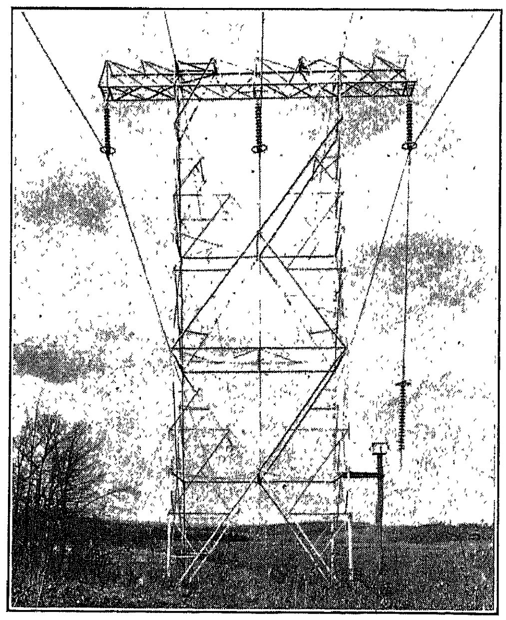


Fig. 3—Typical Surge-voltage Recorder Installation

Type "A" tower potentiometer assembly and surge-voltage recorder installation

A typical surge voltage recorder installation is shown in Fig. 3. The recorder is installed on an elevated platform, which makes it inaccessible to unauthorized persons. Provision for grounding the instrument when it is serviced as well as other features are incorporated

to make the installation safe. This arrangement of the recorder in its sheet metal housing results in a ratio of 60 to 1 between line voltage and instrument voltage for the 20-4 insulator combination, a ratio of 70 to 1 for the 20-3 insulator combination and 90 to 1 for the 20-2 insulator combination. These ratios were determined in the High Voltage Laboratory of the General Electric by calibrating an assembly similar to the field arrangement by impression of surge voltages of known magnitude and wave form. The operation of the surge voltage recorder was fully described before the Institute.[5]

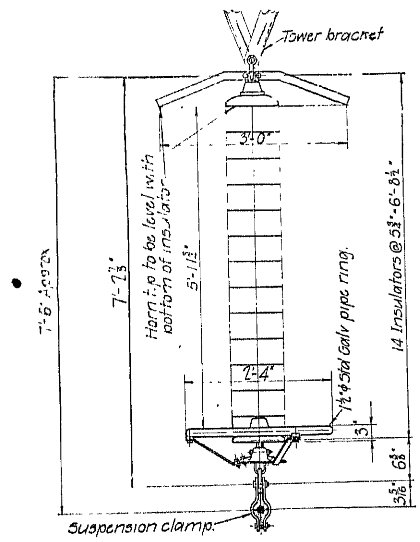


FIG. 4—WALLENPAUPACK-SIEGFRIED 220-KV. LINE

Single string insulator assembly

The Lichtenberg figures recorded on the photographic films of the various instruments were interpreted as to magnitude, nature, and time of occurrence. Simultaneous registrations on several instruments located at different points along the line have been grouped together and designated as a single surge. The magnitude of the surge voltage on the instrument was determined by figure size, and the magnitude of the surge voltage on the conductor was obtained by multiplying the recorded instrument voltage by the potentiometer ratio. All surge values given in this paper refer to the voltage between the line conductor and ground.

Loc. cit. 5.

220-KV. OPERATION OF RECORDERS DURING 1926

The 1926 study will be touched upon briefly to give a more complete perspective of the experience with the line under study.

During the 1926 season, the line was operated in two distinct periods, from April 23 to August 14 at 220 kv., and from August 15, 1926 to March 13, 1927, at 66 kv.

The locations of the instrument were so arranged as to obtain a maximum of data from the limited number of instruments. From Fig. 2 and Table III it may be seen that on phase A there were instruments at each end with three along the line at approximately equal intervals. Phase B was equipped with instruments only at each end. Table III also contains information on potentiometer ratios used.

During this period a number of severe lightning storms passed over or near the line. Before the installations of the instruments, five trip-outs were recorded, and after thirteen trip-outs. After all, except two apparatus trouble trip-outs, the line was returned to service at will after approximately one minute interval. Of these eighteen trip-outs, one was accidental, two were caused by apparatus troubles at Wallenpaupack, two resulted from flashovers between conductor and yard structural steel at Siegfried during lightning storms, and the remaining thirteen were probably caused by line insulator flashovers. At the end of the summer season, a careful examination of each insulator string (by climbing towers) disclosed a total of 24 flashed insulators strings. It was impossible to detect most of these flashed insulators from the ground on inspections made after each trip-out. The insulator flashovers resulted, in most cases, in a slight pitting of caps, rings, and horns, and burned and chipped spots on the porcelain, but in no case was an insulator damaged seriously.

On Fig. 5 is plotted the number of surges against surge magnitude. Of the total of 30 lightning surges recorded, 9 were 10 times normal. Switching resulted in 19 surge records with less than 3 times normal voltage. In addition, there was a total of 14 surges

TABLE III

LOCATION OF SURGE VOLTAGE RECORDERS AND DATES OF THEIR OPERATION

1926

Station	Mile No.	Tower No.	Phase	Tower position	Potentiometer†	Date started	Potentiometer	Date started	Date stopped
					220-Kv. Operation		66-Kv. Operation		
1-3A	1	3	A	West	20-4	7-20	7-1	8-15	10-31
1-3B	1	3	B	Middle	20-4	7-20	7-1	8-15	10-31
17-1A	17	1	A	West	20-4	7-20	7-1	9-26	10-31
32-3A	32	3	A	West	20-4	7-20	9-2	8-26	10-31
48-3A	48	3	A	Middle	20-4	7-19	9-2	8-27	10-31
65-5A	65	5*	A	East	20-4	7-24	9-2	8-23	10-31
65-5B	65	5*	B	Middle	20-4	7-24	9-2	8-23	10-31

*First tower from station.

†"20-4" denotes: 20 disk units between line and ground, with the recorder connected to the cap of the 4th unit from the ground end.

arising from unknown causes, having a maximum value of 1.5 times normal.

66-Kv. Operation of Recorders during 1926

The 66-kv. operation necessitated a change of insulator potentiometer ratio. Table III shows the changes made and the location of the instruments. In changing from the 220-kv. to 66-kv. operation, the line insulation was also changed from a 14-unit string to a 4-unit string by short-circuiting ten of the insulator units. This reduction of line insulation extended for distances of three miles from Wallenpaupack and of three miles from Seigfried. With the exception of the installations at tower 17-1, the line insulation at each surge recorder station and at one tower on either side was similarly reduced.

A total of three 66-kv. trip-outs was caused by lightning flashover of insulators at tower 1–2 at the Wallenpaupack end on which ten units had been short circuited. Surge voltages recorded showed that a maximum of ten times normal voltage occurred during these

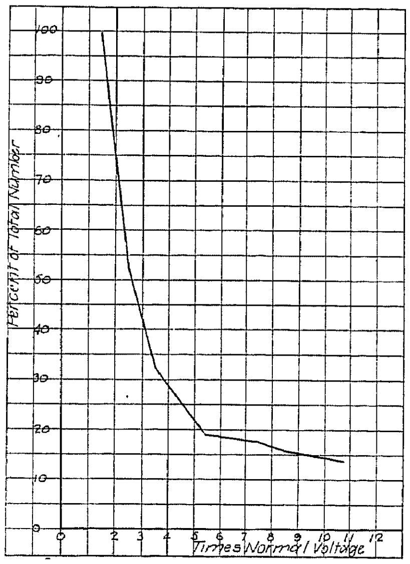


Fig. 5—Magnitude of Surge Voltages 1926

trip-outs. The records from the station at tower 17-1 showed, however, a voltage 29 times normal (based on 66-kv. line voltage), or 1560 kv. This appears to demonstrate that the insulation to ground is a factor in the determination of the maximum voltage to which surge voltages due to lightning may arise.

Preventative and Protective Measures

To secure greater safety to the apparatus against lightning surges of dangerous magnitude, two protective measures were adopted during the spring of 1927:

1. The installation, immediately adjacent to the terminal stations, of lightning protective or spillway gaps of approximately 1300-kv. impulse flashover, and
2. The installation, for distances of approximately five miles, at each end of the line of two overhead ground wires.

For the purpose of studying the effects of overhead ground wires and to further reduce the insulator flashovers, an additional 15-mi. section at the Wallenpaupack end of the line was equipped with these ground wires. Thus the line was protected by ground wires for 20 miles at the Wallenpaupack end, and for five miles at the Siegfried end, leaving the middle section of 40 mi. unprotected. (See Fig. 2). The 20-mile section contains the highest in point of altitude, and in 1926 more than 50 per cent of insulator flashovers occurred on this part of the line. The overhead ground wire was metallically connected to the station grounds, and at the ends away from the transformer stations, it was also effectively grounded through a nest of ground rods. No special provision was made to ground the tower legs.

The protective gaps took the form of insulator assemblies equipped at each end with standard rings having separation of 42.5 in. These gaps were located on the transformer structures and on the first suspension towers at both stations.

1927 Study

During the 1927 season there were three distinct periods of operation: From March 13 to May 27, the line was operated at 220 kv. without overhead ground wires; from May 27 to July 25 it was deenergized and grounded for the purpose of installing the overhead ground wires; and after July 25 operated at 220 kv. with two overhead ground wires as described.

Location of Recorders. By the close of the season, a

TABLE IV
LOCATION OF SURGE VOLTAGE RECORDERS AND DATES OF THEIR OPERATION
1927

Station	Mile No.	Tower No.	Phase	Tower position	Potentiometers†	Date started	Date stopped
Wallenpaupack							
Bus			*A*		20–3	7–26	
1–3A	1	3	*A*	West	20–3	3–12	11–2
1–3B	1	3	*B*	Middle	20–3	3–12	11–2
1–3C	1	3	*C*	East	20–3	4–9	11–2
3–4A	3	4	*A*	West	20–3	7–19	11–2
6–5A	6	5	*A*	West	20–3	7–19	11–2
10–2A	10	2	*A*	West	20–3	7–19	11–2
12–6A	12	6	*A*	West	20–3	7–19	11–2
17–1A	17	1	*A*	West	20–3	4–16	11–2
20–1A	20	1	*A*	West	20–3	7–19	11–2
20–3A	20	3	*A*	West	20–3	7–19	11–2
21–4A	21	4	*A*	West	20–3	7–19	11–2
22–1A	22	1	*A*	West	20–2	7–25	11–2
27–4A	27	4	*A*	West	20–2	7–26	11–2
32–3A	32	3	*A*	West	20–2	4–29	11–2
40–2A	40	2	*A*	West	20–2	7–26	11–2
48–3A	48	3	*A*	Middle	20–2	4–29	11–2
52–4A	52	4	*A*	Middle	20–2	7–24	11–2
56–2A	56	2	*A*	East	20–2	7–24	11–2
61–1A	61	1	*A*	East	20–3	7–24	11–2
61–3A	61	3	*A*	East	20–3	7–24	11–2
62–4A	62	4	*A*	East	20–3	7–24	11–2
64–1A	64	1	*A*	East	20–3	7–24	11–2
65–5A	65*	5	*A*	East	20–3	3–13	10–31
65–5B	65	5	*B*	Middle	20–3	3–13	10–31
65–5C	65	5	*C*	West	20–3	3–29	10–31

*First tower from station.

†"20–3" denotes: 20 disk units between line and ground, with the recorder connected to the cap of the 3rd unit from the ground end.

total of 34 instruments was connected to the line as shown on diagram, Fig. 2, and Table IV. Of this number, 26 were coupled to the line through insulator string potentiometers, and 8 were coupled through two special capacitance transformer bushings. These bushings were located on phase *A* near each transformer station. Both bushings were installed after the close of the lightning season and are not shown on Fig. 2 or Table IV.

Table IV shows the potentiometer ratios used.

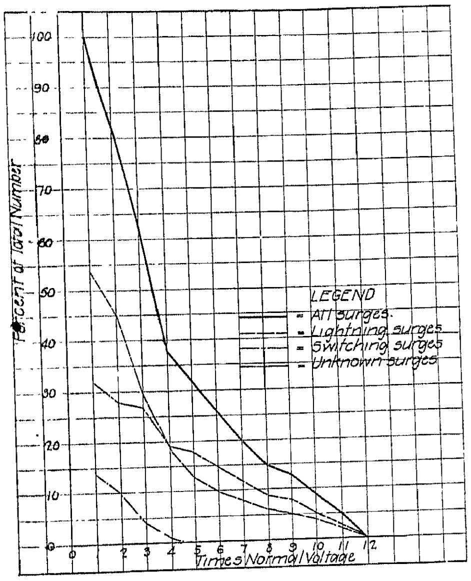


FIG. 6—SURGE CLASSIFIED BY ORIGIN 1927

Nature of Surge Voltages. The Lichtenberg figures recorded were classified according to their character, namely, Type I, II, and III,[6] *i. e.*, very slow, medium, and very abrupt. As practically all of the surges were of Type II, these were further classified as highly damped (HD) and slightly damped (SD).

TABLE V
ORIGIN OF SURGE VOLTAGES
1927

Origin	Number	Highest crest value	
		Times normal	Kv.
Lightning	48	11.7	2100
Switching	21	4.0	720
From unknown causes		7.0	1260
(a) HD	29	4.9	880
(b) SD	51	11.7	2100
Total	149	.	..

The "highly damped" figures are interpreted as being produced by a surge voltage which lasts for only a few reversals of polarity, such as less than five. The "slightly damped" figures are of uncertain origin. They appear to be formed through the continuous application of alternating potentials for the duration of several seconds (long enough to produce film fog). During the period the line was grounded and deenergized no SD figures were recorded. In this period, however, HD figures were quite frequently recorded during lightning storms. This tends to indicate that the normal line excitation is required to produce SD figures.

During the 1927 investigation a total of 149 surges was recorded, ranging in magnitude from 1 to 11.6 times normal (180 kv. to 2100 kv.).

Correlation of the surges with weather and operating data indicated that many of the disturbances had been produced by lightning or switching. Others are of uncertain origin and have been classified as "from unknown causes." Table V and Fig. 6 show the number and maximum voltage of surges classified according to origin.

Lightning Surges. Fig. 7 shows that 56 per cent of the lightning surges exceeded five times normal. The classification as to polarity shows that there are comparatively few unidirectional surge voltages, although their magnitude may be quite high. The majority of lightning surge voltages on this system were oscillatory, with no definite tendency for either the positive or negative wave to be higher.

While the size of figures obtained is indicative of crest voltage values and some information relative to the rate of voltage rise may be obtained from figures characteristics, it is not possible to determine other factors such as relative shape and duration.

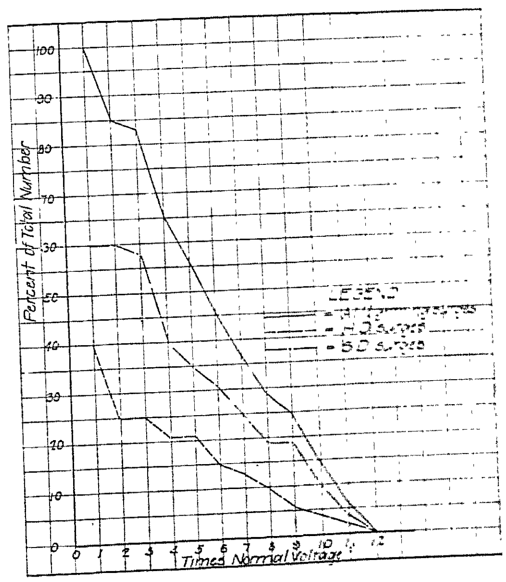


FIG. 7—LIGHTNING SURGES 1927

The curves of Fig. 7 show the relation between number and magnitude of surge voltages recorded. On Table VI it may be seen that all unidirectional voltages recorded have HD characteristics. Negative polarity prevails in the HD oscillatory surge voltages 9 out of 13 cases. The SD figures, however, show only two of the negative polarity out of a total of 30. The HD

6. K. B. McEachron, *Measurements of Transients by Lichtenberg Figures*, A. I. E. E. TRANS., Vol. XLV, 1926, p. 712.

TABLE VI
POLARITY OF HD AND SD SURGE VOLTAGES PRODUCED BY LIGHTNING
1927

Polarity	Number	Highest crest value Times normal
(a) Unidirectional		
HD Positive	2	10
HD Negative	3	1.9
SD Positive	0	0
SD Negative	0	0
(b) Oscillatory		
HD:		
1. H. C. V. *Positive	4	8.6
2. H. C. V. Negative	9	10.0
3. H. C. V. Positive and Negative equal	0	0
SD:		
1. H. C. V. Positive	7	11.7
2. H. C. V. Negative	2	11.6
3. H. C. V. Positive and Negative equal	21	11.6

*H. C. V.—Highest crest value.

figures in no case show equal magnitude of positive and negative voltages, whereas 20 out of the 30 oscillatory SD surge voltages are of equal positive and negative value.

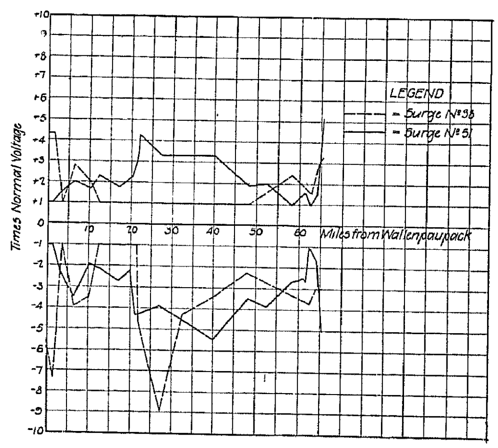


FIG. 8—VOLTAGE PROFILES OF HD LIGHTNING SURGES

Fig. 8 shows the profiles of typical HD surge voltages. Surge No. 38 occurred on July 26 during a general lightning storm after the ground wires were installed. The transformer oil circuit breakers at both ends tripped

TABLE VII
COMPARISON OF SURGE VOLTAGES RECORDED AS TO THE POSITION ON THE TOWER
1927

Phases	Highest crest value times normal A	B	C
At Wallenpaupack—Tower 1-3			
Average voltage	5.7	7.0	5.4
Maximum voltage	7.4	7.0	9.3
At Siegfried—Tower 65-5			
Average voltage	4.8	5.4	3.4
Maximum voltage	7.4	11.6	4.8

with ground current indication at both stations. Relays indicated trouble on phase *C*. The protective gap on phase *C* at the yard structure at Wallenpaupack flashed over, where a number of insulator units was blistered and the shell of one unit broken.

Surge No. 51 occurred on August 13, 1927, during a general lightning storm; however, no trip-outs followed.

These profiles give only an approximate and possibly an incorrect idea of the attenuation along the line. In this connection, it must be borne in mind that there are a great many unknown factors involved. While these curves are based on simultaneous recordings on the instruments as the film moves slowly, there is a possibility that the voltage readings obtained were actually caused by a number of discharges occurring within a short time interval. Further, the recorder actually measures surge potential between line and tower. The location of neutral potential or "good ground" is uncertain. In dealing with surge voltages of very steep wave front, ground resistances, although low, may be effective in determining potentials between line and tower. The position and extent of cloud charge is also unknown.

Due to the short period of operation with the overhead ground wires, it would be premature to draw definite quantitative conclusions.

The comparison of voltages recorded relative to the position on the tower is not definite enough to permit drawing conclusions (Table VII).

During the 1927 season, the line tripped out eight times. One trip-out was caused by an accidental ground on the 66-kv. bus at Siegfried and produced only a small switching surge. The remaining seven trip-outs occurred during lightning storms but only

TABLE VIII
TRIP-OUTS DURING LIGHTNING STORMS
1927

No.	Date and time of trip-outs	Description of failure	Tower	Highest Crest Voltage Times normal	Station	Nature of surge voltage
1	4-21-27, 8:06 P. M.	Ten unit string on *A* and *B* phases flashed	1-2	− 9.3 + 5.3	1-3A	SD Oscillatory
2	4-21-27, 11:05 P. M.	Same as No. 1	1-2	+ 10.0	1-3B	HD Positive
3	5-10-27, 5:26 P. M.	*B* and *C* phases flashed	65-4 1-2	+ 1.0 + 2.3 − 8.6	65-5C 1-3B	HD Oscillatory
4	5-10-27, 5:28 P. M.	Same as No. 3	1-2	Not recorded	..	..
5	7-26-27, 5:09 P. M.	Protective Gap at Wallenpaupack on Phase *C* flashed				
6	7-26-27, 5:14 P. M.	Same as No. 5	1-0	− 9.3	1-3*C*	HD Oscillatory
7	7-27-27, 3:55 P. M.	Location unknown	1-0	Not recorded	..	..
			..	+ 5.3 − 5.3	48-3A	HD Oscillatory

five surges are directly correlated to respective trip-outs. Due to the very short intervals (2 and 5 min.) between two trip-outs at two different times and due to the slow movement of the film, the surge record on the film registered only one surge each time. Table VIII gives the surge voltages correlated as to trip-outs and location of failures.

Surges Due to Switching Operations. Twenty-one surges which coincided with normal switching operations were recorded. Frequently switching produced no records on the surge voltage instruments. This fact is probably due to the low tension switching. The majority of switching operations which produced records were those caused by energizing the line. The maximum value recorded at any time was 4.0 times normal and all were of the HD nature. Most of the switching surges were recorded simultaneously at several stations, although never at all stations.

Unknown Surges. Some of the surges of unknown origin are thought to have been caused by lightning storms not observed by station operators.

CONCLUSIONS

1. During the investigations of 1926 and 1927 surge voltages of a magnitude of 2100 kv. were recorded during lightning storms.
2. The majority of surge voltages due to lightning were oscillatory, although a few HD unidirectional surge voltages were recorded.
3. The highest voltages recorded check fairly well with the prediction made from results of insulator calibration in the laboratory.
4. The line insulation apparently limited the magnitude of lightning surge voltages.
5. Not all of the maximum lightning surge voltages caused power arcs.
6. No definite or reliable information was obtained on attenuation.
7. The quantitative value of protection afforded by the overhead ground wire cannot be deduced from the limited data.
8. The highest surge voltages correlated to switching was four times normal (720 kv.), with practically all surges produced by energizing the line. All such voltages were of the HD nature.
9. Many surge voltages were recorded with no possibility of assigning a definite cause to them. These voltages reached an extreme magnitude of 11.6 times normal (2100 kv.).

FUTURE STUDY

The surge voltage recorder study is being continued in 1928 and it is expected that more data will be obtained than in previous years. The 220-kv. switching also may furnish some valuable and interesting information. Furthermore, with the assistance of laboratory research, it may be possible to determine the relation and condition under which a lightning flashover will be followed by a power arc. This information is of importance in designing lightning proof lines.

Acknowledgment is made to Messrs. C. M. Foust, A. L. Price, F. B. Menger, and W. R. Kleckner for analyzing and correlating the surge voltage data, and to Messrs. A. E. Silver, W. W. Lewis, E. S. Lee, W. E. Lloyd, Jr., and C. A. Jordan for directing the study and criticizing this paper.

Discussion

PAPERS ON SURGE-VOLTAGE INVESTIGATION

(LEWIS, DILLARD, HEMSTREET AND EATON, SPORN, SMELOFF)
DENVER, COLO., JUNE 26, 1928

J. F. Peters: The authors mentioned three types of potentiometers used for this purpose. Mr. Sporn draws some valuable deductions from his experience with two types. Mr. Smeloff refers to the third form, the high-capacitance transformer bushing, in connection with his work during 1927. During one of our voltage investigations we used a condenser-type bushing with a tap brought out from the next-to-bottom condenser layer as a potentiometer. The results were entirely unsatisfactory.

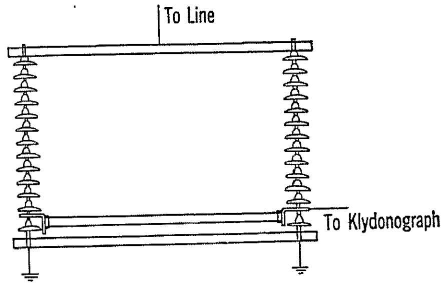


FIG. 1

Due to the high capacitance of the bushing the disturbances for the duration were greatly modified in magnitude as indicated by direct comparison with the results from a ring-type potentiometer in the same station, and I would therefore suggest that in making connections to the line, care be taken not to get too high a capacitance in the potentiometer.

J. H. Cox: The papers presented here are particularly gratifying to the writer, as they add additional weight to most of the conclusions, on the same subject, presented by him, in coauthorship with Messrs. McAuley and Huggins, before this Institute at the Midwinter Convention in 1927.[1]

Mr. Sporn has made an important contribution on the matter of potentiometers. In measuring surge voltages on high-voltage lines, a potentiometer is necessary. Theoretically, either a pure resistance or a pure capacitance is satisfactory. Practically, a resistance is not satisfactory where it must withstand sustained line voltage, and also, for high voltages its physical dimensions become so large that its physical capacity disturbs the voltage distribution. Therefore, the capacity potentiometer is the only one available, and the capacities should be so arranged as to eliminate the effect of any resistance path.

Mr. Sporn has discussed the effects of the leakage path in the insulator-string potentiometer. In another test, with which the writer was connected, pipe-type potentiometers were used but different conditions permitted the desired ratio with the use of only two pipes in the lower group instead of three as shown in Mr. Sporn's paper. The potentiometer used is shown in Fig. 1 herewith. It will be noticed that the klydonograph is tapped across the leakage paths of the two supporting insulator strings.

1. *Klydonograph Surge Investigations*, by Cox, McAuley, and Huggins, A. I. E. E. TRANS., Vol. XLVI, 1927, p. 315.

It was hoped that the capacity of the pipes would be large enough to predominate over the leakage coupling under all conditions. However, it was found that during rainstorms slightly damped figures, of the same nature as those produced by the insulator string potentiometer, were recorded. This was on a grounded neutral system where sustained oscillatory surges had never been recorded in two years' tests with ring-type potentiometers. This undesirable feature was eliminated by short-circuiting the leakage path about the klydonograph in the manner shown in the accompanying Fig. 2.

The pipe-type potentiometer was designed to provide a form more convenient than the ring-type from an installation point of view. The parts are easily provided. Fig. 3 herewith shows a form of pipe-type potentiometer which has recently been devised, which eliminates entirely the leakage path from the klydonograph circuit, and which is even more convenient to install than that shown in Fig. 2.

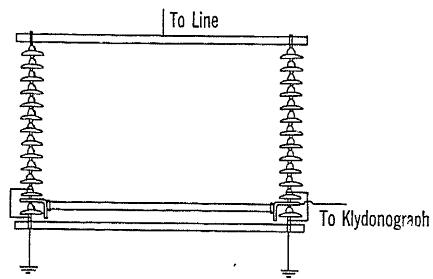


FIG. 2

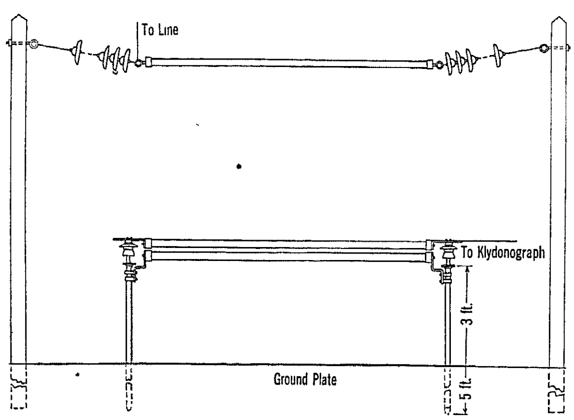


FIG. 3

The writer heartily agrees with Mr. Sporn in his decision to omit all S. D. (slightly damped) figures in his discussion of results. The evidence is quite conclusive that these figures were the result of a change in the ratio of the particular potentiometer used, under certain conditions, and to include them in data on which conclusions are based is misleading. With the exception of the S. D. figures, probably the data furnished with an insulator-string potentiometer are sufficiently accurate. However, the principal object of klydonograph tests is the recording of lightning voltages. These S. D. figures occur during rainstorms which usually accompany lightning. Figures occurring at this time, of course, obscure the legitimate figures recorded by voltages actually existing on the line. Therefore, with the elimination of the S. D. figures some of the most desired data are automatically eliminated. Hence, although the cheapness of the insulator-string potentiometer makes it particularly attractive, the writer does not feel that its use is justified.

F. C. Hanker: The need for more accurate information on the fundamentals of lightning phenomena has long been recognized, but no reliable recording device was available until the development and introduction of the klydonograph by Mr. Peters in 1923 made possible for the first time, the measurement of lightning and other surge voltages with a reasonable degree of accuracy. The characteristic which makes this device of particular value for the work, is that while it will operate for a week or more without attention, it will record the magnitude and polarity of voltages, the duration of which may be less than a microsecond and which may occur at any time.

It is desirable to obtain more complete information on surges caused on transmission lines than it is possible to obtain with the klydonograph. We secure reasonably accurate information on the magnitude within the limits of line insulation but in order to develop remedial devices more completely, it is important to establish other characteristics such as shape of wave front, duration, shape of wave tail, polarity, and effect of location of the stroke.

The Westinghouse Company, in cooperation with the Aluminum Company of America, is starting a lightning investigation in Tennessee using the form of cathode-ray oscillograph which was announced by Dr. Nordinder in his papers presented before the Franklin Institute and at the 1928 Winter Convention of this Institute.[2] In both of these presentations, he has given records of actual surge voltages recorded on an operating transmission circuit. This instrument, with other accessories used in the investigation, will yield all the information which has been lacking from the extensive klydonograph surveys that have been made during the past two years.

Due to the uncertainty of the occurrence of lightning, the complete story cannot be obtained in a short time. Existing circuits have limitations in dielectric strength that make it impossible to establish definitely the maximum voltages that are impressed on the circuit. It is expected that oscillograms obtained with the instrument now in operation will give sufficient data to permit establishing the complete wave form with a reasonable degree of accuracy and will point the way toward future procedure in obtaining the complete answer to the problem.

L. L. Perry: The papers show that on well designed transmission lines surges as high as ten or twelve times normal voltage must be expected in lightning country.

With regard to these conditions, I should like to ask Mr. Lewis these questions:

1. Would further developments in choke coils materially reduce the voltages reaching the arresters? Possibly it might increase.

2. To what percentage of normal voltage will a modern arrester limit the surge?

3. Does he recommend eliminating the arrester and making circuit breakers and transformers so that their insulation will withstand ten or twelve times normal without flashover or failure?

I should also like to ask him if he can supplement Table IV by the average height of conductor for line H-8?

I should also like to ask Mr. Foust from the operating records what percentage of trip-outs on one circuit involve the second circuit?

A. C. Austin: It is interesting to note that some of the conclusions drawn through a study of the performance of the insulator are apparently corroborated by the recent studies. Some years ago it was evident that where a line was under-insulated or had a number of faulty insulators, switching surges of appreciable magnitude apparently traversed the whole line, whereas lightning was localized. This was evident from the fact that a line might pass through a number of severe electrical storms before tripping out. In trying to energize the line again, however, it was sometimes necessary to avoid all switching surges and build up the voltage before the line would stay in. The

2. *The Cathode Oscillograph as Used in the Study of Lightning and Other Surges on Transmission Lines*, A. I. E. E. Quarterly TRANS., Vol 47, April 1928, p. 446.

conclusions reached were that the much higher disturbances produced by lightning were localized so that they did not affect a faulty insulator which was readily picked out by the lower voltage surge occasioned by switching, but which affected practically the whole line.

The need of more exact information as to the wave front or exact history of the disturbance on the line is still apparent. Tests in the laboratory indicate that many flashovers may take place at from 50 per cent to 60 per cent of the crest value occurring on the tail of the wave. The cathode-ray oscillograph shows that the flashover of an insulator may take place under a variety of conditions, depending upon the magnitude and duration of the wave. Both line troubles as well as tests in the high-voltage laboratory indicate that not only will the wave front produced by lightning vary considerably, but that the wave front for a single discharge is likely to vary over a very wide range.

To obtain records on the transmission line for actual conditions is not an easy problem, for a record which will cover a period of from 10 to 50 microseconds may not give the information on certain parts of the wave or voltage rise in sufficient detail. While apparently perfect oscillograph records may be obtained, it is necessary that these records are of the condition set up on the line by lightning and not a record of a disturbance set up in or greatly modified by the leads or coupling to the transmission line.

Tests made during the past year go to show that potentials above 800 kv. peak drop very rapidly and are usually attended by an oscillation during the decay of the charge. In most cases the discharge does not develop to the point where a power arc will follow until 10 or 15 microseconds after the crest is reached, the actual flashover taking place at a voltage of not more than 50 or 60 per cent of the crest voltage. From this it would appear that any scheme which will increase the time lag of the insulator or increase the attenuation will result in lower flashovers. On the other hand, tower or insulator construction or the attachment of electrodes which will reduce the time lag will result in increasing the number of flashovers.

The steepest wave fronts, although reaching very high values, may not cause as many flashovers as wave fronts at very much less slope and magnitude. This is particularly true where the dissipation or absorption of the charge is high.

Philip Sporn: Mr. Lewis's statement that the voltage on a line is limited by the flashover strength of the line insulators, ought to be modified, I think, to include not only the insulators but the structure itself, which, in turn, of course, includes the connection to ground. Mr. Peek has shown that the flashover value of a string of insulators increases with the amount of resistance to ground in series with that string and it is very important that in all discussions this be kept to the forefront as on no other basis have we been able to date to explain many phenomena that are clearly explained this way.

As regards the attenuation and the formula presented by Mr. Lewis, this is a fine attempt to get attenuation down on a mathematical basis but I do not believe that sufficient data have been gathered together for anybody to be able to say definitely that this is an exact and proved relationship. Some of the data that we obtained on investigations not mentioned in our paper would seem to indicate a much higher attenuation on lightning surges than the one given in the equation developed by Messrs. Foust and Menger. It is to be hoped that the work which is being carried on this year will give us more data on the subject.

C. M. Faust: Having been closely identified with the analyzing of the films from the surge recorders, I thought it might be somewhat interesting to try to explain and amplify and clarify possibly our methods of attack. For that purpose I have prepared a little chart. All surges were subject to two classifications, one with reference to nature or polarity characteristic and the other with regard to wave front. This chart may serve to explain these classifications.

All surges—	Nature of Polarity Characteristic	Unidirectional	Positive polarity Negative polarity
		Oscillatory	Highly damped (Predominantly pos.) (Predominantly neg.) Medium damped Slightly damped

All surges—Type	I. Slow wave front II. Medium wave front III. Fast wave front

Now with regard to this sort of classification and with particular reference to unidirectional or highly damped surges, there are two cases of field registration of interest.

1. Surges measured at only one station.
2. Surges measured at several stations.

Under the first case, a surge was readily classified with reference to the above chart. With regard to the second case, however, there were instances wherein station records disagreed, for example, indicated unidirectional at one station and oscillation but highly damped at others. With regard to the general classification of such a surge, two methods were followed:

1. Surge classified as oscillatory when registered as oscillatory at any one station.
2. Surge classified as to nature with regard to the polarity characteristic at the station where highest voltage registration was obtained.

The second classification appears to have particular advantage if the polarity of the induced charges is of interest. First, because reflection conditions may complicate the record at remote stations and secondly, because the switching surge due to the automatic trip-out cannot be separated from the lightning surge itself.

As both the above methods of classification have been used by the authors in preparing their papers, comparison of results must be performed with this in mind.

J. F. Foote: The formula for the attenuation of surges is probably of correct form for surges of a particular range of frequency. The results showing wide extent of M. D. surges and equally extensive H. D. switching surges would indicate that some other factors than voltage and line constants may affect attenuation. Would not further investigation of the possible effect of varying wave fronts probably show that the formula should include a wave front term or factor?

In stating that we may expect small trouble from M. D. surges because they are usually of less value than the impulse flashover of insulators, should we not recall that the M. D. surge may not be similar to the impulse wave upon which the insulator flashover value is based? It would seem reasonable to expect the flashover value of the insulator under the stress of such waves to be intermediate between the value obtained with an extremely steep wave front and that obtained at 60 cycles. In other words, the flashover value may be anywhere within the range of, say, three times to ten times the normal voltage, depending on the frequency of the surge. Thus if M. D. surges of moderately high frequency be encountered it is conceivable that flashovers may occur even at moderate amplitudes.

The conclusions regarding the effectiveness of choke coils do not seem entirely justified by the data given. That is, if it is meant that the amplitude of the voltage surge continuing beyond the choke coil tends to be in the order of 25 per cent less than the surge would be if the coil were omitted, the method of measurement used is inconclusive, since the voltage measured on the line side of the choke coil is not the voltage of the impressed surge, but this voltage increased by the partial reflection of this wave by the coil.

A choke coil is not a unidirectional valve nor is it more than a partial reflecting agent. Part of the impressed wave is probably reflected and the remainder passes through the coil. Should the transmitted surge then encounter another reflecting agent,

as it usually will, in the way of a transformer winding or open switch, full or partial reflection of this wave will occur. If the distance between the choke coil and the second reflecting agent be short, attenuation will be small and the surge will strike the choke coil from the rear, as it were, being again partially reflected. Thus it is very possible that oscillations may build up in the short section beyond the choke coil, producing voltages in excess of the original surge.

The data in Mr. Sporn's paper indicate that in four out of ten cases this voltage did build up to greater values than even that of the partially reflected surge outside the coil. The other six show lower voltages beyond the coil than the reflected voltage in front of the coil, but it is not shown what the unreflected voltage might have been, and possibly the reduction was not a reduction in fact.

For many years the lightning-arrester engineers have regarded the choke coil as an accessory to assist in quick and certain gap break-down. However, the arrester is usually purchased to protect station, not line equipment, and to isolate such equipment from the arrester by the choke coil seems illogical in view of the considerations noted above.

Fred O. McMillan: It is interesting to note in Mr. Lewis' paper that the only points that are at any considerable distance from the drawn curve of Fig. 10 are those for surges 38 and 40, which were on the Pennsylvania Power and Light Company's system. Since this company's line has design constants different from the New England Power Company's line, it is to be expected that the constant k for equations (1) and (2) would be quite different for these two surges.

I should like to ask Mr. Lewis to explain more fully why the voltages on the ground wire and tower were comparatively low. One would expect that in the case of very steep wave fronts the voltage rise would be very high until the reflected wave from ground wipes out the initial wave. It would appear that the only explanation of the low ground-wire voltages found must be in having waves of relatively sloping wave fronts.

Harold Michener: The Vincent 220,000-volt line was built without a ground wire. The southern half of it has been in operation for nearly two years and the complete line since last November.

Two months ago we had about six flashovers from lightning. We decided to put on two ground wires. We were careful, however, to tell our management that we didn't expect the ground wires to stop all the trouble from lightning.

The observations made at the time were rather interesting. Some of our men were working on a road near the location of the trouble and they reported that they could see streamers of fire, corona streamers, of some considerable length extending from the wires before the flashover occurred. The storm went on across that section of the old Big Creek lines immediately north of Vestal substation and caused no trouble on them.

This was pointed out as showing the value of the ground wire under the supposition that the two parallel old Big Creek lines were each equipped with one ground wire in this section and that the Vincent line was not. However, this proved to be the section in which there is about a 20-mi. gap in the ground wire on one of the old Big Creek lines. What we really had was the Vincent line in trouble from lightning, the storm passing on across the old Big Creek lines with lightning striking near on both sides of them and causing only fluctuations in the meters at Vestal even though one of them did not have a ground wire in this section.

Another thing of interest in that section of the old Big Creek lines through the San Joaquin Valley is that the only case of lightning trouble we have had there was on a tower equipped with two ground wires.

These facts, as we see them, only go to show that we cannot place too much dependence on the ground wires, and the fact that we are putting ground wires on the Vincent lines since we had the trouble with lightning shows we believe they will be of some benefit.

I rather expected to find more unanimity of opinion in regard to ground wires. I had gained the impression during the last two or three years that almost everyone was swinging to the belief that ground wires are a real protection. I think they are, but still there are things that seem a little doubtful about it.

E. S. Fields: The Union Gas and Electric Company of Cincinnati has been experimenting with a device for interrupting the flashover current before the protective relays operate to cause a trip-out of the transmission circuit with which some of you are probably familiar. Fig. 4 herewith shows the device in the present stage of its development for 66-kv. construction. A standard grading ring is installed at the conductor at the bottom of the insulator string. At the top of the string two 33-kv. expulsion fuses are installed in the position of arcing horns.

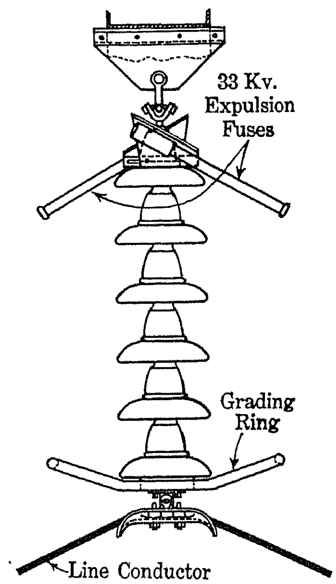


Fig. 4

In order to insure that the flashovers will take place from the end of the fused horn to the grading ring, the length and position of the fused horns and the dimensions of the grading ring have been determined from experiments conducted in the high-voltage laboratory with the impulse generator.

When a flashover occurs it strikes from the tip of the fuse to the grading ring. The power current that follows is interrupted by the operation of the expulsion fuse, usually in the first half cycle.

Sixty miles of 66-kv. line were equipped with this device in 1926 and the performance of this initial installation has led to the installation of the device on fifty miles of additional 66-kv. circuit this year.

During the summer of 1926, 77 per cent of the flashovers occurring on the original 60 mi. of 66-kv. line were interrupted by the fuses without service interruptions on the circuit. So far only 66-kv. circuits have been equipped with this device.

A. O. Austin: Both Mr. Smeloff and Mr. Michener made very interesting statements in connection with the use of the ground wire. Mr. Foote also mentioned the danger from flashover for voltages much lower than the crest voltages induced by lightning. It is these lower voltage flashovers which offer the most serious problem for the very long high-voltage transmission line.

It is interesting to note that the recent klydonograph records as well as tests in the laboratory go to show that the attenuation or dissipation of the charge is very rapid at the higher voltages, but that the attenuation drops off very quickly as the voltage is

reduced. By applying this information to the operation of the line we are able to explain some of the apparently contradictory performance of the ground wire.

The ground wire functions primarily through its absorbing electrostatic capacity which tends to keep down the rise in potential for a given charge on the power conductor. While the presence of the ground wire reduces the quantity of the charge, on the power conductor, this is comparatively small where the separation of the conductors is large. Where no ground wire is used, a very high induced voltage or one above three-quarters of a million to one million volts is dissipated very rapidly as corona loss. If in the same installation a ground wire were installed such that the induced voltage on the power conductor would not rise above three-quarters of a million volts below which the corona loss is relatively small, it naturally follows that there would be more energy to set up a surge or traveling wave, which would have greater amplitude at a distance than where a large part of the energy was dissipated. In view of this, the increasing use of low-resistance ground wires must be watched very carefully as their use is likely to have the same effect upon the transmission line as the use of more limber springs and balloon tires had upon the automobile. While balloon tires and more limber springs greatly reduced the shock, it was necessary to provide shock absorbers in order to eliminate the resulting oscillation which otherwise more than offset the reduction in the intensity of the initial shock.

Where the ground wire has the properties of the shock absorber, it will not only reduce the crest voltage or bump, but will dissipate the energy stored in the power conductor.

Where the resistance of the ground wire is low, the current induced in the ground wire by a traveling wave or oscillation will create but small loss so that a low-resistance ground wire will not have the dissipating or shock-absorbing properties of a high-resistance ground wire. If we are to obtain the benefit of a low-resistance ground wire both from the standpoint of reducing the crest voltage and through the absorption of energy in the traveling wave, it is necessary to adopt a new scheme of installation. In this scheme it is proposed to sectionalize and insulate the ground wire, forcing the induced currents over discharge gaps which will dissipate energy. In order that the ground wire may hold down the crest voltage in the vicinity of the disturbance, a shunt gap is provided at the insulated supports. This shunt gap discharges and reduces the potential from ground wire to earth. An installation of this kind not only keeps down the maximum voltage in the vicinity of the disturbance, but can be made to absorb the traveling wave or oscillation. The absorption of energy tends to cut down the time-voltage effect, tending to flash the insulator and thereby reduces the tendency to flash at a distance. The absorption of energy will also be beneficial in keeping down the magnitude of the surge entering the station. From the electrical standpoint, resistance in the ground wire may be of material advantage and where low-resistance ground wires are used, it would seem that provision should be made so that they will dissipate the energy of the traveling waves or oscillations.

Where ground wires are located near stations, attention should be given to developing the electrostatic capacity between ground wire and conductors as far as possible. This increased electrostatic capacity together with the electrostatic capacity of the bus structure and connected equipment will do much to keep down the maximum voltage in the station. It would seem that the increased electrostatic capacity of the station is a much greater factor in keeping down the maximum voltage than the impedance of a choke coil. In extra high-voltage transformers, more dependence is placed in the circuit upon absorbing resistances than upon reactance coils. As a matter of fact, where break-downs are quite frequent with reactance coils, these break-downs have disappeared where absorbing resistances are used. Where an absorbing resistance cannot be placed between the line and a large station, an absorbing resistance can be placed in a ground wire. As the energy must come from the power conductor, the same general result will be accomplished as in the case where the absorbing resistance is used directly in the circuit.

W. W. Parker: (communicated after adjournment) I feel in very strong agreement with J. F. Peters' suggestion that the potentiometer used in connection with the klydonograph requires some special investigation and further research. We got some rather startling results from a klydonograph installation on our 132-kv. system last January, which led to some investigations. It was found that positive figures can be produced by sprinkling water over the potentiometer, and by momentarily bridging out one of the insulators forming part of the potentiometer string. Each figure obtained by sprinkling the potentiometer is positive. The rays radiate out from the center with no evidence of any negative figures. Some of these figures are as high as fifteen times normal.

The potentiometer consists of five Faradon condenser-type insulators in series, the klydonograph being connected across the last insulator. The last insulator is approximately ten times the capacity of the others.

C. F. Harding: (communicated after adjournment) The data recorded and summarized in the paper by Messrs. Hemstreet and Eaton provide one more distinct advance in the investigation of high-voltage surges and the analysis of their causes. The surge recorders have apparently provided more information regarding the number, magnitude, and locality of such surges upon transmission lines than any instruments have furnished which have been available previous to this time.

However, such an instrument is admittedly very approximate in its quantitative measurement, particularly with respect to the steepness of the wave front and duration of the tail of the surge, and is likely to be qualitatively misleading with respect to initial polarity and indication of the oscillatory nature of the discharge. The large number of surges which were recorded with almost equal magnitude at all stations, apparently having medium damped characteristics and yet rising to 7.7 times normal line voltage and coinciding with switch trip-outs, is, of course, such as to cause the more serious and widespread interruption to service. These should therefore be studied most thoroughly in future investigations. Fortunately, such surges may now be recorded and analyzed by means of the cathode-ray oscillograph and the polarity, magnitude, and duration of the medium and slightly damped tails of the surge may be more accurately determined and studied.

The contribution of this paper to the much discussed subject of the protective value of the ground wire, furnishing for the first time concrete test data of parallel exposures under similar conditions both with and without the ground wire, has been greatly needed to bring to a definite conclusion the arguments of past years which have been based upon exposures of different types in various localities and the resulting opinions of engineers necessarily dependent upon rather meager test data. These test data are significant not only because of their proof of the protective feature of the ground wire, but particularly because of the reduction in the number of surges which ranged from four to eight times normal line voltage and the apparent elimination of those between eight and eleven times normal which appeared upon the parallel line. Furthermore, the importance of thorough grounding of the ground wire at each tower has been demonstrated by the test voltages accumulated at the center of the span.

Although the conclusion is recorded with reference to Figs. 11 and 12 that "no definite relation exists between the magnitude of surge voltages measured and conductor height," it would appear from inspection of these graphs that the upper wire on both lines is withstanding more and higher voltage surges than the lower wires, particularly for surges up to five or six times normal. It would be of interest to know if the original data, or those not

included in these charts, tend to neutralize the value of such a conclusion.

J. E. Clem: (communicated after adjournment) Mr. Lewis in his paper gives the maximum voltage found as resulting from switching, but gives no data in regard to the length of the wave front. The wave front should be known so that new lines may be designed with enough insulation to withstand these surges. This discussion will present some data which should help in deciding whether 60 cycle or impulse strength applied when considering the voltages produced by switching surges.

In Table V, Lewis gives the maximum voltages found due to switching and in the text states that load switching is not severe and that switching off is more severe than switching on. Although not mentioned specifically the voltages due to opening a short circuit are included in the tabulation. It is also stated that these surges are usually highly damped and therefore of short duration. It is seen from this table that the highest voltage is about 5 times the normal crest voltage line to neutral. Since this ratio is not exceeded over the operating range from 110 kv. to 220 kv. it can be used safely for design.

TABLE A

WAVE FRONT OF SWITCHING SURGES
NEW ENGLAND POWER CO.
Normal Voltage Line to Neutral = 90 Kv.

Between 100 Kv. and 200 Kv.		Between 200 Kv. and 300 Kv.		Between 300 Kv. and—	
Kv.	Front Mc. S	Kv.	Front Mc. S	Kv.	Front Mc. S
120	$10^5 - 10^6$	210	$10^1 - 10^5$		
120	$10^5 - 10^6$	240	$10^5 - 10^6$		
120	$10^5 - 10^6$	240	$10^5 - 10^6$		
120	$10^5 - 10^7$	240	$10^5 - 10^6$		
120	$10^5 - 10^6$	220	$10^3 - 10^5$		
120	$10^5 -$	220	$10^3 - 10^5$		
120	$10^5 - 10^7$	200	$10^4 - 10^5$		
140	$10^5 -$	240	$10^4 - 10^5$		
110	$10^4 - 10^5$	240	$10^4 - 10^5$		
160	$10^4 - 10^5$				
150	$10^1 - 10^5$	270	$10^3 - 10^5$	360	$10^2 - 10^5$
150	$10^1 - 10^5$	280	$10^3 - 10^5$		
150	$10^5 - 10^6$	260	$10^3 - 10^5$		
150	$10^5 -$	260	$10^3 - 10^5$		
150	$10^4 - 10^5$	270	$10^3 - 10^5$		
160	$10^1 - 10^5$				
180	$10^4 - 10^5$				
180	$10^4 - 10^5$				
180	$10^5 - 10^7$				

TABLE B

WAVE FRONT OF SWITCHING SURGES
PENNSYLVANIA POWER & LIGHT CO
Normal Voltage Line to Neutral = 180 Kv.

Between 300 Kv. and 400 Kv.		Between 400 Kv. and 500 Kv.		Between 500 Kv. and 600 Kv.		Between 600 Kv. and—	
Kv.	Front Mc. S	Kv.	Front Mc. S	Kv.	Front Mc. S	Kv.	Front Mc. S
340	$10^4 - 10^5$	410	$10^4 - 10^5$	540	$10^3 - 10^5$	630	$10^3 - 10^5$
320	?	410	$10^1 - 10^5$	540	$10^3 - 10^5$	600	$10^3 - 10^5$
		410	$10^4 - 10^5$				
		410	$10^4 - 10^5$				
		410	$10^4 - 10^5$				
360	$10^4 - 10^5$	480	$10^4 - 10^5$	575	$10^3 - 10^5$	720	$10^2 - 10^6$
340	$10^4 - 10^5$	450	$10^3 - 10^5$	560	$10^4 - 10^5$		
340	$10^4 - 10^5$	480	$10^4 - 10^5$				
360	$10^4 - 10^5$						
360	$10^4 - 10^5$						

TABLE C

WAVE FRONT OF SWITCHING SURGES
OHIO POWER CO.
Normal Voltage Line to Neutral = 108 Kv. Crest

Between 200 Kv. and 300 Kv.		Between 300 Kv. and 400 Kv.		Between 400 Kv. and 500 Kv.		Between 500 Kv. and	
Kv.	Front Mc. S	Kv.	Front Mc. S	Kv.	Front Mc. S	Kv.	Front Mc. S
200	?	−300	F?	−410	F10	+550	$10 - 10^4$
240	10^5	+300	10^4	+420	$10^2 - 10^3$	+550	$10 - 10^4$
−240	10^5	+320	$10^1 - 10^5$	440	$10^3 - 10^5$	+520	$10 - 10^2$
−240	$10^5 - 10^6$	+320	$10^4 - 10^5$	−440	$10^2 - 10^5$		
+220	$10^4 - 10^5$	−330	$10^5 - 10^6$	+430	$10^3 - 10^5$		
+200	$10^5 - 10^6$	+300	$10^5 - 10^6$	+400	$10^2 - 10^5$		
+200	10^5	+320	$10^5 - 10^6$	+430	$10^2 - 10^5$		
−250	$10^4 - 10^5$	+345	$10^3 - 10^5$	+410	$10 - 10^2$		
−210	$10^4 - 10^5$	−300	10^3				
230	10^5	310	$10^3 - 10^5$				
−250	$10^4 - 10^5$	−330	$10^4 - 10^5$				
−230	$10^3 - 10^4$	−330	10^3				
−290	$10^4 - 10^5$	−360	$10^3 - 10^4$	+450	$10 - 100$		
−295	F10^3	+370	$10^3 - 10^5$	−480	$10^2 - 10^4$		
270	F100 ?	−395	F100	+480	$10 - 10^2$		
+280	$10^4 - 10^5$	−350	$10^3 - 10^5$				
−280	$10^4 - 10^5$	+395	$10^3 - 10^1$				
−270	$10^4 - 10^5$	+380	F100				
+290	10^4	370	10^3				
−295	$10^4 - 10^5$	−380	$10^3 - 10^5$				
−275	F10^4	−370	$10^3 - 10^5$				
−293	$10^3 - 10^5$	350	$10^3 - 10^5$				
−270	$10^4 - 10^5$	+360	$10^3 - 10^4$				
280	10^4	360	10^2				
−260	$10^4 - 10^5$	+370	F10^3				

The accompaning three tabulations give an analysis of switching surges found on three of the systems mentioned in Table V. The data have been tabulated to show the magnitude of the crest voltage and the time to reach the crest; that is, the wave front. The wave front was obtained by the method outlined in Lewis's paper. A study of these data indicates that at the lower voltages the wave fronts are relatively long, while at the higher voltages there might be said to be a tendency toward shorter wave fronts. Although all the surges, except one, above four times normal could have had a wave front as fast as 100 microseconds, it doubtless would be better to consider them all slow and use the 60-cycle flashover strength of the insulators in figuring the number of units required to prevent flashover from switching surges.

These switching surges may happen when the line insulators are wet and this should be considered. For a standard precipitation of 0.2 in. rain per minute the 60-cycle flashover is approximately 80 per cent of the dry flashover. This precipitation is not rain but is really a deluge. At half the standard precipitation the flashover is about 7 per cent higher, according to Peek, and for the ordinary heavy rainstorms is no doubt somewhat higher.

The lightning flashover of a string of insulators is the same wet as dry which indicates that the effect of moisture decreases as the wave front grows shorter. In view of the fact that the surges having a magnitude of five times normal probably have a wave front faster than the 60-cycle wave front, it is quite possible that the effect of rain is somewhat less than at 60 cycles. Also Wade and Smith in an article entitled "Time Lag of Insulators," *Elec. World*, Aug. 18, 1928, give data which indicate that the flashover voltage of suspension insulators obtained with a wave front corresponding to 60 cycles may be somewhat higher than that obtained by the usual method of determining the 60-cycle flashover voltage. These two facts indicate that the ratio of wet to dry flashover for these switching surges will be higher than for 60 cycles. From the foregoing it appears that the dry 60-cycle flashover voltage of the insulators can be used in estimating insulation required for switching surges.

Studies of existing systems have shown that the average line insulation will stand about six times normal voltage. This is

enough to withstand any low-frequency disturbances to which the lines may be subjected, whether due to dropping of load, switching, or arcing grounds. It appears that a line insulated for five times normal lag voltage will not flash over during switching transients, but since existing lines have an average of six times, it would be better to use six times normal leg voltage as the required insulation strength at 60 cycles.

R. H. George: (communicated after adjournment) The percentage of apparently oscillatory discharges recorded by Messrs. Hemstreet and Eaton seems quite high, but as pointed out, this may be due largely to the limitations of the surge recorder rather than to actual oscillatory surges. Some of these records may result from a series of successive discharges from cloud to earth similar to those illustrated in Dr. Humphreys' book "Physics of the Air," pages 368-372. Dr. Humphreys shows one photograph taken by Larsen with a revolving-mirror camera in which six successive discharges take place along the same path at intervals of from 4 to 10 milliseconds. If such a series of discharges took place in the vicinity of a transmission line, the rapid fluctuations in the field might give rise to records of reversed polarity although the actual discharges were in one direction.

It is quite probable that the question of oscillatory surges on transmission lines can only be solved by the use of the cathode-ray oscillograph, or the use of the oscillograph and surge recorder together.

W. W. Lewis: Mr. Perry asked about the effect of choke coils on the voltage reaching the arresters. That is what we are trying to find out in our investigation. All the data we have on the subject at present are given in Mr. Sporn's and my papers. The data are rather confusing and do not indicate definitely whether choke coils are beneficial or not. We are, however, going to use them until we know more about the subject.

Mr. Perry also asked to what percentage of normal voltage a modern arrester will limit a surge. This has been very well answered by Mr. K. B. McEachron in a paper entitled "Protection of Station Equipment on High-Voltage Transmission Lines" which appeared in the *General Electric Review* of May 1928. In this paper it is shown that oxide-film arresters limit the voltage of a surge to certain values which depend on the wave front of the surge. These values vary from about 1 kv. per cell to about 1.8 kv. per cell. The last-named value is the voltage corresponding to the steepest wave fronts, *i. e.*, of the order of one-fourth microsecond. Such a front is steeper than any that we have been able to measure on transmission lines and corresponds with the wave in Mr. Peek's laboratory which we have used as a reference in giving the flashover value of insulator strings.

From this statement it will be apparent that the fewer the cells used, the better the protection obtained. A certain minimum number of cells is required, however, to prevent the arrester from failing under 60-cycle voltage when the voltage runs away due to the dropping of load. If this runaway voltage can be maintained at a low value, then the number of cells may be decreased and the protection will be improved.

Mr. Perry also asked that Table IV be supplemented by the average height of conductor for Line H-8. This average height, I believe, is about 45 ft.

In Mr. Foote's discussion he refers to the 60-cycle flashover value of line insulation as about three times normal. On the average system the 60-cycle flashover is usually about six times normal, *i. e.*, six times the crest value of the line-to-neutral voltage. For example: On Mr. Foote's own 140-kv. system, normal voltage is about 114-kv. crest value line-to-neutral. The 60-cycle flashover of ten standard disks is about 765-kv. crest value, or about 6.7 times normal. The impulse flashover with steep wave is in the neighborhood of 1400 kv. or about 12 times normal. An examination will disclose that the majority of transmission lines are insulated for at least six times normal, 60 cycle voltage, and from 10 to 14 times normal against impulse flashover.

The flashover voltage of a string of insulators varies from the 60-cycle value to a very high value under impulse. Any number of impulse values may be obtained, depending on the steepness of the wave front and the duration of the wave. The figure of 10 to 14 times normal mentioned as impulse flashover is based on a particular wave of steep front and long tail. If we had a steeper wave we might even get a higher value. As shown in Table IV of my paper, the highest voltages recorded in the 1927 investigation vary from 7 to 12 times normal, which check fairly well with the estimated impulse flashover.

In regard to Mr. Michener's discussion: the resistance of the tower footing has a great deal of effect on the operation of the ground wire. If the tower footing has a high resistance the ground wire is, in effect, an insulated wire, and will do very little good in reducing surge voltage.

In the particular territory discussed by Mr. Michener, it might be that the soil is composed largely of sand and rocks. This condition will give a very high tower-footing resistance which not only nullifies the grounding of the ground wire but apparently has the effect of increasing the height of the tower. In other words, a high ground resistance indicates that the water level is considerably below the earth surface and the tower in effect is much higher than indicated by the height above the earth's surface itself. This allows lightning to build up a higher voltage on the conductors than would be expected. Mr. J. G. Hemstreet brought out this effect very well in a paper entitled *Recent Investigation of Transmission Line Operation*, which appeared in A. I. E. E., TRANS., Vol. 46, 1927, page 835.

J. R. Eaton: There is one point in connection with safety that has been emphasized in the report on the Pennsylvania Power and Light Company presented by Mr. Smeloff.

The line was grounded at numerous places during the installation of a ground wire. Even with this line grounded at various places, there were very high voltages recorded—I think over a million volts. On the Consumers' line we recorded over 35,000 volts at mid-span of a ground wire, where, of course, it was grounded at both ends of the span.

That certainly emphasizes the necessity of grounding a line at the point where men are working on it, especially under lightning conditions. A ground that is located even a few spans away certainly does not offer adequate protection to men who are working on the line.

Someone asked for an explanation of the fact that surges recorded at mid-span of the ground wire had low values compared with that recorded simultaneously on the line wire. On the ground wire the maximum voltage recorded was 35 kv. at mid-span while at the tower it was several hundred kv. It is possible that the surge originated at some point down the line, and the transient traveled along the conductor without being reduced in value to any great extent, whereas on the ground wire, the section on which the surge recorder was connected was in a weak part of the field and received only a small part of the voltage.

In some recent inspections we have found two distinct kinds of burns on our insulators. There is one type which we feel sure is caused by a power arc. This resembles that produced by laying a cigarette on a varnished surface. That undoubtedly comes from the power arc.

There is another type of burn on the procelain which might be described as appearing as though some thin molasses had been spilled near the cap of the insulator and then run in a narrow stream to the end of the insulator. This type of burn has been observed on insulators which have been flashed over by impulses from lightning generators as well as on insulators in the field. We feel reasonably sure these burns are caused by the lightning discharge itself. Burns of this type are frequently found where the power arc type of burn is also found, indicating

that possibly there had been a lightning flashover followed by the power arc.

In some cases, however, every unit in a string will have the lightning burn on the porcelain, showing almost a complete cascade of the lightning discharge, but there will be no power-arc burns at all. That may be an explanation of the fact that in some cases we have recorded very high voltages on lines without having them trip out. Apparently the power arc did not follow the lightning flashover.

J. G. Hemstreet: The investigations that are being made on the various transmission systems and in the laboratories are gradually determining exact conditions which create perhaps the greatest hazard to power transmission.

The klydonograph has been of great value in determining the magnitude of the surges set up and has quite definitely shown that surges due to causes other than lightning are not so serious as was thought a few years ago. The results of the klydonograph investigations as shown by these papers have been a little disappointing due to the uncertainty of the meaning of some of the figures recorded. However, this difficulty has been done away with and with the proper type of potentiometer, a better set of records should be obtained by these instruments.

We believe that some of the most valuable information has been obtained by careful inspections of transmission lines and by keeping records of the number of insulator flashovers found by these inspections. The insulator string and its performance under the abnormal conditions in the lines is, in the last word, the real indicator of the severity of the surges that are taking place and it would be well if more of the operating companies would make these careful investigations so that a greater quantity of data will be available for study.

The cathode-ray oscillograph seems to offer a means of securing information as to the steepness of the wave front and other characteristics of the surges that are under investigation. It is our understanding that an oscillograph of this type, together with other instruments, is to be used by the Westinghouse Electric and Manufacturing Company in securing data on one of the high-voltage lines in Tennessee and that the General Electric Company are making a somewhat similar setup on a line in Pennsylvania. The Consumers Power Company in continuing its investigation of lightning disturbances, has obtained the use of a type of cathode-ray oscillograph which has been developed in the High Voltage Laboratory of Purdue University. This instrument will be connected to the lines of this company and it is hoped that more exact information as to the character of the surges on the system will be secured. This, together with the investigation on other systems along the same line, will perhaps give us information that will be of great value in connection with the design of transmission lines and substations.

Philip Sporn: Mr. Michener's point with regard to the effectiveness of the ground wire, I think, is very well taken. The papers, as a whole, do not bring out the effectiveness of the ground wire as clearly as do other operating data and I should like to refer Mr. Michener to the series of papers that has been presented during the last three years before the Institute, on the lightning experience that we had with the Philo-Canton line both before and after ground wires were installed, which throw some light on the ground wire's effectiveness.

Mr. Foote brought up a point with regard to choke coils. When we first started our klydonograph layout to study the effectiveness of the choke coils we had pretty high hopes. We thought we would get come definite information either pro or con. The first thing that we ran into was a few surges that came in where we found on one side of the choke coil some 200 kv. positive and on the other side we found the same negative, a reversal of polarity taking place through the choke coil. On going to the next tower out from the station we found that it was still positive. We did not believe this. There are so many surges that can be superimposed one on top of the other, or combined due to reflection, and since the klydonograph records only the one maximum voltage which exists, the limited information that we have obtained so far cannot possibly be conclusive. However, we do believe that this much has been shown. In so far as it can be said that the choke coil is either a benefit or a hindrance in connection with a lightning arrester the data showed definitely that it is certainly no worse than neutral and very often beneficial. Theory, of course, checks that up also.

Mr. Austin made the statement that attenuation is much less rapid with the ground wire than without it. This is obviously not so. He is right if he means that due to the fact that where a ground wire exists the possible amplitude of the wave is initially cut down and therefore the rate of attenuation on this reduced wave is much smaller than it would have been on the wave without a ground wire. Otherwise he is not right, since the ground wire helps reduce the amplitude of the wave by acting as an absorbing medium.

N. N. Smeloff: The type of potentiometer used on our system produces slightly damped figures. We have not discarded these figures from our study, but classified them and used them. These uses were made with a reservation, *i. e.*, it is without doubt now established that the slightly damped figures are produced by 60-cycle potential and this type of potentiometer; however, the highly damped figures may be present, but obscured by the slightly damped figures. This has been proved by the fact that during some trip-outs and flashovers of the line, only the slightly damped figures were obtained on the recorder films.

The study during 1928 is more extensive: more instruments and additional 220-kv. line are used. The potentiometers for the surge-voltage recorders have been modified in such a manner that no slightly damped surges are produced that would obscure the recorder films.

It would be rather premature to draw conclusions about the operation of our new 220-kv. line. It went through just about two months of lightning season operation without trip-outs. Surge-voltage recorders are installed and we expect to obtain valuable data. On the old line, Wallenpaupack-Siegfried, we again had several flashovers. The flashovers occurred on the unprotected section of the line as well as on the section where the overhead ground wire was installed. So again we are not in a position at this time, to make any definite conclusions on the value of overhead ground-wire protection.

Research

ANNUAL REPORT OF THE COMMITTEE ON RESEARCH*

To the Board of Directors:

1. The Research Committee

In order to increase the activities and usefulness of the committee it seemed desirable to appoint working subcommittees to take charge of the several important divisions of the work. The following have been appointed:

Subcommittee on Placing of Research Subjects with Suitable Persons and Organizations—(D. W. Roper, Chairman).

Subcommittee on Training of Research Men—(V. Bush, Chairman).

The membership of the committee should be so chosen that a considerable percentage of the membership of the subcommittees will overlap from year to year. The appointment of several other working subcommittees is under consideration. It is hoped that the working committees of the Research Committee will eventually make it as effective in the research field as similar working committees have made the Standards Committee in the standardization field. It is suggested that consideration be give to changing the Research Committee from a technical committee to a standing committee.

2. Examples of Outstanding Research During the Year

The spectacular contribution to the communication art in the past year has been television. This has a particular interest from the standpoint of research since it was made possible by improvements in mechanical and electrical facilities that have sprung directly from research work, instances of which are improvements in photoelectric cells, in methods of amplification, in gaseous discharge lamps for producing visible effects from rapidly changing electrical signals, and improved methods of synchronization of widely separated points.

Other developments are the Knowles tube and its application to the televox, starting electrical equipment at a distance, and the development of a 50 million-cycle tube with a 10-kw. output. The increase in power of many American and foreign radio stations, making them international in their effects, raised the question as to whether or not the national standards of radio frequency of various governments were in agreement. During the past year a check was made by Dr. Dellinger of the Bureau of Standards in the National Laboratories of England, France, Italy, and Germany by means of the temperature controlled piezo-oscillator. The average difference was only 0.03 kilocycles in 1000. This is much smaller than the variation of 0.5 kilocycles allowed broadcasting stations in this country.

A radio beacon system establishing an invisible but infallible course along which aviators can fly regardless of weather conditions, has been sufficiently perfected by the Bureau of Standards so that routine use of it on regular airways is beginning.

A most impressive and historic event took place at the Winter Convention this year. Through the courtesy of the American Telephone and Telegraph Company and the British Post Office a joint meeting took place over the radio telephone between the Institution of Electrical Engineers of Great Britain meeting in London and the American Institute of Electrical Engineers meeting in New York.

There has been a number of researches during the past year of a fundamental nature. Particular mention might be made of the work of Davison and Germer regarding the diffraction of electrons by crystals of nickel. They prove that electrons behave at reflection as though they had wavelengths dependent upon their velocity. The discovery and measurement by J. B. Johnson of an electromotive force due to the thermal agitation within conducting materials is also of importance.

Among new tools which increase the scope of fundamental work in physics and engineering might be mentioned the operation by Coolidge of three cathode ray tubes in series at 900,000 volts.

A lightning generator producing impulses of over 3,500,000 volts also offers an important tool for the extension of fundamental work in physics and engineering.

Considerable important work on insulation measurements and lightning measurements on transmission lines is being carried out.

An analysis of the important fundamental research of the country shows that a fairly large percentage is still being done by the large industrial laboratories such as those of the American Telephone and Telegraph, the Westinghouse, and the General Electric Companies.

3. Research Organizations

While the large manufacturing companies are still doing a considerable percentage of the important fundamental research, there are indications that our colleges and other organizations will play an increasingly

*COMMITTEE ON RESEARCH:

F. W. Peek, Jr., Chairman.

H. D. Arnold,	W. P. Dobson,	E. W. Rice, Jr.,
Edward Bennett,	V. Karapetoff,	D. W. Roper,
V. Bush,	A. E. Kennelly,	C. H. Sharp,
E. H. Colpitts,	S. M. Kintner,	C. E. Skinner,
W. F. Davidson,	M. G. Lloyd,	R. W. Sorensen,
W. A. Del Mar	C. E. Magnusson,	J. B. Whitehead.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

important part, as they should. It is reassuring that funds are more readily available than ever before.

An important new factor in research has been given us in the Bartol Foundation, the result of a large bequest. Dr. Swann, director of this organization, which will undoubtedly have a very important influence on future American research, has kindly supplied the following information regarding it.

"The Bartol Research Foundation of the Franklin Institute is at present located in three houses at 127 No. 19 St., Philadelphia. These houses were made over a few years ago for laboratory purposes, and comprise ten research rooms, a library, glass blowing room, shop, and accommodations for storage battery equipment, etc.

"The present site is only temporary, pending the completion of a new laboratory. By an arrangement with Swarthmore College, it has been decided to build upon the campus of the college. By this arrangement the laboratory secures a site free from the disturbances of traffic and protected as regards its surroundings. It secures a congenial academic atmosphere such as most of its members have been accustomed to. On the other hand, while there is no affiliation to the college itself, the college feels that our presence will rebound to its advantage in many ways, and we hope and feel that this will be so.

"The laboratory will be about 110 ft. long and 50 ft. wide, comprising a basement, first and second floor, and a subbasement large enough to accommodate one spectroscopic room. The attic will also accommodate two rooms. The basement floor includes a large machine shop, wood shop, a glass blowing shop, and a battery installation, together with a room for miscellaneous technical operations.

"The first floor will be devoted to research laboratories and a workshop for the fellows, and the director's laboratory and offices. On the second floor there will be an apparatus room, a lecture room and large library, an optical shop, small office and research rooms, and the attic will provide for a chemical laboratory. The whole is designed to accommodate about ten or fifteen fellows together with the director, and research assistants. At the present time the technical staff comprises one instrument maker, one mechanic and an apprentice, also a full time glass blower and a general utility man.

"The main activities of the laboratory will be directed to the investigation of scientific problems pertaining to the fundamentals of electrical science. This is, of course, rather a wide field and comprises practically the whole field of modern atomic structure under its head.

"While the laboratory is primarily for research, it is proposed to provide in it such conditions for continued mental development as are desirable for young men of the post Ph. D. type. The director and the individual fellows take turns in lecturing to the group upon various phases of modern physics, particularly in relation to atomic structure. The Bartol Foundation has been fortunate in having many lecturers from American institutions, and a fund has been appropriated for the purpose of bringing from time to time distinguished physicists to stay here for a period of two or three months and give the laboratory the benefit of their intellectual contact.

"At the present time, the laboratory is accommodating six fellows on its payroll, one National Research Council fellow, a guest fellow, and one research assistant. It is possible that two or more National Research Council fellows will be here next year. Since October 1, 1927, eight publications of the Bartol Foundation have appeared in the *Journal of the Franklin Institute* and six publications of the results of investigations at the laboratory have been presented before the American Physical Society.

The following investigations are at present under way at the laboratory.

1. An investigation on the reflection of atoms of atomic hydrogen from crystal surfaces.
2. The production of, and characteristic properties of X-rays produced by protons.
3. An attempt to detect a magnetic field resulting from the rapid rotation of a copper sphere.
4. An investigation concerning the pulling of electrons out of metal under intense electric fields.
5. An investigation of the loss of velocity of electrons as a result of the production of characteristic X-rays in the passage of the electrons through thin metallic films.
6. A series of investigations pertaining to the mechanisms involved in the production of the electric arc between carbon electrodes and metal electrodes.
7. The design of an apparatus for the production of high electrical potentials.
8. A series of investigations having to do with the effect of high-frequency fields on optical and allied properties of transparent media.
9. An investigation of the nature of excitation of various lines in the mercury arc.
10. An investigation of the part played by cosmic radiation in the production of radio activity.
11. An investigation on the electrical conductivity of non-aqueous solutions of solvents.
12. A theoretical investigation on the scattering of X-rays by matter.
13. The preparation of a paper involving the results of observations of the cosmic radiation, made at Pike's Peak and New Haven."

* * * * *

The Public Utilities are entering the research field and are not only supplying money to colleges, but are also operating research laboratories. As an example, the Utilities Research Commission, made up of representatives of the utilities of which Mr. Samuel Insull is the head, has arranged for investigation of cable insulation at the University of Illinois, of lightning protection at Purdue, and of properties of insulation at the University of Chicago, etc.

Important work is being carried on in insulation by

committees of the National Research Council, the N. E. L. A., etc.

The Research Committee of the Institute serves as the Advisory Committee on Electrical Engineering to the National Research Council and is also closely cooperating with the Engineering Foundation.

4. The Training of Research Workers

Results in research depend more upon men than money and laboratories. It is still a fact that in spite of organized research and group working in large laboratories, outstanding results are generally due to the genius or inspiration of the right man. While such men cannot be manufactured in our colleges, natural ability can be developed under the proper influence. Apparently the colleges are making progress, as indicated by the report of Professor V. Bush, Chairman of the Subcommittee on Training of Research Engineers, which follows:

"There is a considerable increase in the emphasis being placed on graduate study and hence on engineering research, which is an important part of such study, in schools of advanced standing among the technical educational institutions of the country. The total graduate enrolment in engineering colleges on the basis of the statistics of the United States Bureau of Education was 1114 in 1925-26, 1566 in 1926-27, and 1669 in 1927-28. The principal branches are civil, mechanical, electrical, and chemical engineering and in 1925-26 these four included 807 out of the 1114. During the three years cited the figures for civil engineering are 156, 240, and 266; those for mechanical engineering 256, 206, and 240; and those for electrical engineering, 281, 434, and 468. Of course these figures include many graduate students in technical schools where there is little important research being carried on; and perhaps only 30 or 40 per cent are in contact with research of a high order in their institutions. Still it is evident that there is an increasing tendency toward work of this nature in technical schools, and that this tendency is particularly marked in recent years among students of electrical engineering.

"It is believed that this tendency toward graduate study and research is a healthy development, and that its growth should be encouraged by industry and by the profession. Perhaps the greatest encouragement that can be given is for the students to learn that real achievement in advanced work is highly regarded by the profession wherever such is the case. There is no doubt that the recent analysis by the Bell System of the correlation between high grades in college and success in later work on their staff, as presented by President W. S. Gifford in Harper's Magazine for May 1928, will have a real vital influence in encouraging a scholarly attitude on the part of undergraduates generally. Similarly, if the industry and profession find by experience that graduate study of a serious sort is worth while for students of outstanding ability, the knowledge that such a conviction exists will be of the greatest value in raising the tone of graduate study and research in the engineering colleges. It is to be hoped, therefore, that the membership of the Institute will watch this development of graduate study and research with interest, and that, if they believe it is a desirable thing for the progress of electrical engineering, they will make known their convictions in an effective manner.

"Direct aid of such work by industries is, of course, valuable, particularly when the research carried on at educational institutions is carefully correlated with the regular instruction so that the full pedogogical benefit of working in a research atmosphere is obtained. Some years ago, for example, when graduate study in engineering schools was just beginning to grow, the American Telephone and Telegraph Company contributed directly to electrical engineering research at the Massachusetts Institute of Technology, and the work resulting was conducted in close liaison with the instructional program of that institution. The research results obtained were themselves worth while, but more important was, undoubtedly, the influence upon the student body and the early exposure of students to the research point of view.

"It is becoming increasingly evident in recent years that electrical engineering is adopting and applying more and more of mathematical and applied physics and chemistry. Hand in hand with this adoption must go the training of research workers of high calibre who have the engineering attitude, if the greatest progress is to be made. Industrial research is being well carried on by the industry, but the principal supply of research workers must come from the colleges; and, as electrical engineering becomes more and more complex, the training in advanced study and research in the technical schools must continue to expand as it has done in recent years to meet the need."

F. W. Peek, *Chairman.*

Electrophysics

ANNUAL REPORT OF THE ELECTROPHYSICS COMMITTEE*

To the Board of Directors:

The personnel of the Committee and its general policies have been practically the same as during the preceding Institute year, so that this report is essentially a continuation of the last year's report. A steady endeavor has been made during the year to connect some practical engineering problems with the achievements and efforts of modern physics, both experimental and mathematical. In these endeavors we have been materially assisted by the two liaison representatives of the American Physical Society, authorized by the Board of Directors in 1927. As a further step in the same direction, the committee arranged for a general lecture on *The Nature of the Electric Arc* which was ably delivered by Professor K. T. Compton at the 1927 Summer Convention in Detroit.

The success of this lecture led to an authorization of another lecture at the 1928 Winter Convention. The subject of this lecture was *The Earth's Electric Charge,* and it was delivered by Dr. W. F. G. Swann of the Bartol Research Foundation. This lecture was also quite successful, and as a result a lecture on geophysics, by Dr. C. A. Heiland, was presented at the Denver convention. The committee recommends that a lecture on some topic in "border sciences," such as physics, chemistry, mechanics, and mathematics, be scheduled at all our large conventions, as a stimulus to young engineers in fostering the progress of the art and as a preventative against in-breeding. In particular, for the next Winter Convention, the committee suggests a topic on spectrum analysis in application to the constitution of the stars. During such a lecture, much of the latest progress in the atomic structure could be explained on a specific problem.

Papers Presented

Quite a number of papers related to electrophysics have been presented at or scheduled for various Institute meetings during the period covered by this report. The titles and authors of several of these papers are mentioned below in connection with the individual topics. The papers themselves will be found in the Journal and the Transactions for 1927 and 1928.

*Committee on Electrophysics:
V. Karapetoff, Chairman,
O. E. Buckley, Vice-Chairman,
Carl Kinsley, Secretary.

V. Bush,	C. L. Fortescue,	R. A. Millikan,
F. M. Clark,	A. Hund,	C. A. Nickle,
W. D. Coolidge,	W. B. Kouwenhoven,	J. Slepian,
W. F. Davidson,	K. B. McEachron,	Irving B. Smith,
J. F. H. Douglas,		J. B. Whitehead.

Liaison Representatives of American Physical Society
W. F. G. Swann   A. P. Wills

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Electrical Discharges in Gases

Disruptive Discharges. A simple relation for determining the voltage across a spark-gap during the course of breakdown has been given, but the constant entering into this relation has been found to vary widely under different conditions of test. (Toepler, Mueller, *Arch. f. Elektrotech.*). Cathode ray oscillographic study of spark-gaps also gives results incompatible with the Toepler spark constant (Tamm, *Arch. f. Elektrotech.*). Photographs of incompleted sparks indicate the need for modification of the Townsend sparkover theory for high voltages at atmospheric pressures. (Torok, A. I. E. E. Quarterly, April 1928). The distortion of the electric field by a space charge in the early stages of the formation of the spark may be important (Loeb, *Journ. of Franklin Inst.*). Whether negative ions are generated near the cathode by collisions of positive ions with gas molecules, or by radiation acting photoelectrically upon the cathode, has been actively debated. (Taylor, Townsend, *Phil. Mag.*). Experiments on "three-point spark-gaps" favor the photoelectric action. (Morgan, Thomson, *Phil. Mag.*). Lowering of the sparking potential under sustained high-frequency applied voltage has been observed. (Reukema, A. I. E. E., Trans., 1927).

Corona. Further studies on the mechanism of corona, bringing out the part played by space charges, have been made (Carroll & Lusignan, Quarterly Trans. 1928, Peek, A. I. E. E.Trans., 1927). A quantitative theory giving excellent checks with observations has been developed for the d-c. corona. (Holm *Arch. f. Elektrotech.*)

Arcs. There has been great interest in the theory of the electric arc. The possibility of arcs with cathodes too cold for thermionic emission is being accepted. Application of the heat balance method of determining the proportion of current carried by electrons from the cathode does not agree with the thermionic theory of the cathode. (Compton, A. I. E. E. Trans., 1927). In applying the heat balance method, the experimental results of Van Voorhis (*Phys. Rev.*) on the heat of neutralization of positive ions are important. The view that electrons are drawn from the cathode by very high electrostatic gradients maintained by space charges is being favored (Compton, Prince, A. I. E. E. Trans., 1927). In this connection, however, Rosario (*Journ. of Frank. Inst.*) describes experiments casting doubt on the ability of electric fields, of the order of magnitude here postulated, to draw electrons from a cold cathode.

Short-Time Phenomena

The study of transients occurring on transmission lines, with the aid of the klydonograph and surge

recorder, has been actively pursued during the past year. Although much valuable information has been obtained, yet it is becoming increasingly apparent that more information is needed with respect to the form of the transients than the Lichtenberg figures have given.

The cathode ray oscillograph is the only device available which will give an oscillographic record of the volt-time relations of short-time transients. Norinder has applied the oscillograph to this work successfully. Additional work is being undertaken in this country so that valuable contributions along this line may be looked for in the next few years.

The study of lightning and of transients due to lightning still continues to occupy the interest of physicists and engineers. Several laboratories in different parts of the world are being equipped to study high-voltage transients. Crest voltages of over 3,000,000 volts have been reached. Spark-gap measurements, insulator flashover, strength of insulation, as in transformers, and the strength of wood poles, are some of the problems being actively studied.

Valuable research has been accomplished in connection with the protection of oil tanks and reservoirs against lightning strokes. Still more work is needed in order that the mechanism of the lightning discharge may be more fully understood. Some studies have been reported in which the mechanism of the breakdown of a sphere-gap and a needle-gap under transient conditions has been studied experimentally. (Torok, see above; Zinszer, *Phil. Mag.*, 1928). Additional research of this nature would be of great value.

High-Voltage Research

Further study has been made during the past year of corona, using the cathode ray oscillograph. Valuable contributions with respect to the space charge of corona have been made. Last year marked the first 220,000 volt transmission to be installed in the East and this year this system has been considerably extended. Studies of lightning phenomena are being continued on this 220,000-volt system with the promise of obtaining useful data.

Ferromagnetism

Among the advances which have been made in the field of ferromagnetism during the past year are the following:

1. Further studies of the magnetization and magnetostriction of single crystals of iron (Dussler and Gerlach) and of nickel (Kaya and Masiyama, and Sucksmith, Potter, and Broadway), show the dependence of these properties on crystallographic direction.

2. The permeability of iron has been reported in two papers (Wait, and Gutton and Mihul) to have no peculiarly small value in alternating fields of radio frequencies, contrary to the results of Wwedensky.

3. Magnetic viscosity, the time lag in magnetization, has been investigated experimentally by Lapp.

4. DeWaard in a mathematical treatment has attempted to account for ferromagnetic properties as dependent on crystal form and crystal lattice.

5. Some evidence has been obtained by X-ray analysis of films of iron in magnetic fields as to the ultimate nature of magnetism. T. D. Yensen, *Phys. Rev.*, Vol. 31, April 1928, p. 714.

6. An X-ray analysis of thin films of electrolytic iron gave results supporting the hypothesis of the atomic nature of magnetism. A circular X-ray diffraction pattern resulting from the randomly oriented minute crystals of iron in a film were examined with the film unmagnetized and also magnetized. No difference in the pattern due to magnetization could be detected, a result apparently explicable only on the assumption that the fundamental magnetic unit is atomic in character.

7. A notable contribution to the literature of ferromagnetism, of particular interest to electrical engineers, is T. F. Wall's book on Applied Magnetism.

8. A new method of obtaining strong magnetic fields has been described; P. Kapitza, *Roy. Soc. Proc.*, 115, Aug. 1927, p. 658.

9. A magnetic field within a coil of wire was produced by sending through the coil a current with amplitude in some cases as high as 72,000 amperes. As a source of current, a single-phase a-c. generator of the turbo alternator type was used, a half cycle only being utilized. A magnetic field within the coil, of about 320,000 gauss, was developed for about 1/100 of a sec. throughout a volume of 2 cu. cm. The chief difficulty encountered was in designing a coil to withstand the extremely large mechanical distorting forces of electrodynamic origin. Experiments on the change of resistance of bismuth due to a field of 300,000 gauss showed a thousandfold increase in resistance at the temperature of liquid air and a fiftyfold increase at room temperature.

Radio and Electro Acoustics

The following were live topics during the year under review:

A. *Radio:*

1. Propagation phenomena; effect of solar activity, ionized regions, Heaviside layer, etc., on radio transmission;
2. Precision measurement of frequency;
3. Television without wires;
4. Radio on trains;
5. Miscellaneous apparatus, such as field intensity sets, tube generators, etc.

B. *Acoustic matters:*

1. Super-sonic waves in gases, liquids, and solids;*

*By super-sonic waves are meant longitudinal vibrations similar to sound waves, but of frequencies much beyond the audible range, reaching as high as 400,000 oscillations per second and beyond. Some striking effects of such waves, as well as practical applications, have been demonstrated by Prof. R. W. Wood of Johns Hopkins University.

2. Analysis of vowel and other sounds by means of technical devices;
3. Bessel and exponential horns for sound power;
4. Loudspeaker and receiver tests;
5. Sound transmission through building materials.

C. Generation of Sinusoidal Sound Waves:

A beat-frequency generator, for producing audio currents which are practically sinusoidal, has been constructed by the Bureau of Standards. The frequency is adjustable and stabilized by means of a piezoelectric quartz disk and can be directly read off on a scale. The holder containing the piezoelectric element has a hand control for changing the frequency of the quartz disk by a small amount (a fraction of a cycle to several cycles).

On account of the piezoelectric control, it is possible to reset the calibration for the frequency for most any useful B voltage on the tubes producing the two high-frequency currents which beat with each other. The resetting can be carried on without any standard, by means of a filament rheostat common to both oscillator tubes. The slow visible vibrations on the meter for the anode current of the piezoelectric oscillator are utilized for the resetting of the scale.

A thermostatic control is provided for very accurate work. Two filter detector circuits are provided for obtaining audio currents of a good wave shape and keeping any high-frequency currents away from the load branch. A specially designed power amplifier is available. The same is used when more energy is required.

Magnetic and Electrostatic Fields

Magnetic field distribution has been studied in application to various problems in electrical machinery, such as reluctance, wave form of e. m. f., pole-face losses, inductance, armature reaction, etc.

An important advance in our knowledge of magnetic fields is the work of Dr. Th. Lehmann. In the *Revue Générale de l'Electricité,* Dec. 24, 1927, he discusses the effects of pole saturation and interpolar iron on interpolar flux, considering as before the non-lamellar character of the field. The non-lamellar field, also treated in some recent articles in the *General Electric Review,* and *Electric Journal,* is related to eddy-currents, which were considered by Roth, Schenkhag, and Strutt. Roth has discussed the case of slot-conductors in the *Revue Générale de l'Electricité* of Sept. 27, 1927. H. Schenkhag and M. Strutt have discussed the flux distribution in busbar conductors, in the *Archiv für Elektrotechnik.* Dr. E. Weber, in the *Archiv für Elektrotechnik* of Nov. 17, 1927, has reported on the effect of the pole-shoe shape on flux distribution and wave form of e. m. f. Dr. Th. Lehmann has pointed out a needed modification of the "Minimum-Reluctance Rule" in computing mechanical forces of the magnetic field.

The electrostatic field of force within high-tension transformers has been investigated by Dr. J. Labus in the *Archiv für Elektrotechnik* for Nov. 3rd, 1927. The method used was that of the functions of a complex variable, and several new cases have been solved. W. Wittwer in the *Archiv* for April 7, 1927, reported on a combined mathematical and experimental method, by which he has studied the correlation between the breakdown strength and the geometrical factor, for the cases of insulation bounded by electrodes with sharp edges.

Dielectrics

In view of the existence of a Committee on Electrical Insulation of the National Research Council (Professor J. B. Whitehead, Chairman) with which the writer of the present report has kept in close touch through several members common to both committees, the activities of the Electrophysics Committee in the field of dielectrics so far have mainly consisted in cooperating with the other committee. Those interested in details of various research projects and actual investigations in the field of dielectrics, should consult the Annual Reports of the Committee on Electrical Insulation. Among the principal problems under discussion are the following: (a) Dielectric phase difference, loss and absorption; (b) Ionization, polarization, and physical theories; (c) Dielectric strength and breakdown; (d) Dielectric constant; (e) Resistivity and conductivity; (f) Flashover; (g) Physical and chemical changes due to electric stress; (h) Properties of particular materials as related to manufacturing processes; (i) Special problems on the insulation of communication systems.

At the summer convention of the A. I. E. E. in Detroit, in 1927, a serial report of the Committee on Electrical Insulation covered the literature on Electric Strength of Solid and Liquid Dielectrics. During the past year there have been few contributions on this subject in American literature and the foreign press has contained a few articles. Apparently more attention is being given to other phases of dielectric behavior and to consideration of various series of dielectric phenomena. A serial report of the Committee on Insulation of the National Research Council prepared by Dr. Curtis covers the subject of electrical resistivity of insulating materials, and we have had a paper on the Theory of Imperfect Solid Dielectrics by Dr. Malti. Bush and Moon have reported on a device for automatically obtaining a large number of determinations of dielectric strength as a means of eliminating some of the uncertainties due to the wide variations between individual readings. This seems to offer considerable promise if applied to other materials than those studied by these authors.

A paper by Murnaghan throws additional light on the Boltzmann-Hopkinson principle of superposition as applied to dielectrics and is indicative of the attention which is being given in several laboratories to the phenomenon of absorption.

A considerable number of thorough-going researches

are under way dealing with various phases of impregnated paper insulation as used in high-voltage cables, and the results of some of these have appeared in print as papers before the Institute, or those of rather more restricted circulation. This includes the paper presented by the Detroit Edison Company before the Association of Edison Illuminating Companies.

Joffé, at Leningrad, and some of his coworkers are studying dielectric absorption in its relation to polarization and conductivity of crystals. This work is very significant in its indication of the nature of dielectric absorption in some of its manifestations. He shows that in certain crystals there is an initial constant conductivity and that the final absorption phenomenon is due to a polarization which may be treated independently of the conductivity. Some of his coworkers have attempted to show that this initial conductivity is sufficient to account for the dielectric loss.

A number of experimental researches on dielectrics is being conducted at various universities, as will be seen from the following partial list:

Harvard University, under Prof. C. L. Dawes—"Gaseous Ionization in Impregnated Paper Insulation."

Massachusetts Institute of Technology, under Prof. V. Bush—"The Properties of Papers used for Impregnated Paper Insulation."

Johns Hopkins University, under Prof. J. B. Whitehead—"Influence of Variations in Drying and Evacuating Processes on the Properties of Impregnated Paper."

University of Wisconsin, under Prof. Edward Bennett—"Relation between Dielectric Losses and Anomalous Charging Current."

University of Illinois, under Prof. E. B. Paine,—"Ionization in High-Voltage Cables."

The Johns Hopkins University, under Prof. W. B. Kouwenhoven,—"Phase Difference in Air Condensers."

University of Wisconsin, under Professor Edward Bennett,—"Properties of Dielectrics."

The Johns Hopkins University, under Prof. J. B. Whitehead,—"Fundamental Study of Dielectric Absorption of Waxes and Oils."

Cornell University, under Professor V. Karapetoff,—"Study of Oils used in High-Tension Cables."

These researches are supported for the most part by the National Electric Light Association, Association of Edison Illuminating Companies, the Engineering Foundation, or individual public utilities.

Mechanical Solutions of Engineering Problems

An Integraph has been developed by Professor V. Bush and his coworkers at Massachusetts Institute of Technology, for a mechanical solution of rather complicated differential and integral equations occuring in various branches of engineering. The machine has already been applied to several problems; for details see *Journal of Franklin Institute*, Jan. 1927, p. 63, and Nov. 1927, p. 575; also *Physical Review*, Feb. 1927, p. 337.

A mechanical device which quantitatively imitates electric transients in an interconnected power system, was described in a paper by R. C. Bergvall and P. H. Robinson at the Baltimore Regional Convention of the A. I. E. E., (Quarterly Trans., July 1928).

Temperature Measurements

On May 12, 1927, the following resolution was passed by the Standards Committee of the A. I. E. E.: "That the broad question of standards for the technique of temperature measurement be referred to the Electrophysics Committee for investigation and report." In accordance with this request, the chairman has taken steps to ascertain the views of some interested parties and obtained a list of persons competent to serve on a subcommittee on Temperature Measurements. The problem is quite broad and the proposed subcommittee will have to investigate various methods of accurate temperature measurement, used in practise and in scientific work, find out their limitations and advantages, and select those which are sufficiently accurate without being unduly intricate. The chairman of this subcommittee has not been chosen as yet, but the matter has been submitted to the Bureau of Standards in the hope that a member of their staff may serve as chairman and thus be an impartial connecting link among the various industrial groups and scientific specialists represented on the subcommittee. It may be of interest to mention that there is a Committee on Heat Transmission of the National Research Council, and among its subcommittees there is one on Temperature Measurements. It is hoped that the proposed subcommittee will cooperate with this subcommittee.

Some Points of Contact Between Electrophysics and Electrical Engineering

A pure physicist usually studies whatever interests him most, or for whatever problem he has the necessary experimental and mathematical equipment. On the other hand, an applied physicist, or an engineer working on the border line between engineering and physics, is naturally limited to those topics which promise a more or less immediate application. The following list indicates some of such topics, although undoubtedly there are many more not included in it. It is hoped that this list may stimulate some younger engineers to undertake further "importation" of methods and results from the domain of physics into that of engineering.

Arcs; their theory, spectroscopy, phenomena at the cathode, stability, range of voltage, distribution of potential.

Atmospheric Electricity; theories of; methods of measurement; prediction of disturbances; thunderstorms, aurora borealis, ionized conducting upper layer of the atmosphere, the nature of terrestrial magnetism.

A-C. Bridges; various types, sources of power, detectors, inaccuracies, shielding.

Bushings for Extra-high Voltages; theory of stress

distribution; design, experimental investigation of stresses, and safety against flashovers.

Cables; capacitance, heating, insulation resistance, ionization, study of oil and paper, stresses, joints, sheath and armor.

Capacitance; computation of, for lines, cables, plates, spheres, antennas, and irregular shapes. Measurement of capacitance in difficult cases; design of condensers for extra-high voltages and large capacitance.

Cathode Rays; their theory, production, measurements, application to oscillograph, penetration through matter, production of X-rays.

Circuits; general theory of; Heaviside's operational calculus; Carson's theories.

Conduction of Electricity in gases, liquids, and solids; fundamental theories, crucial experiments.

Contact Phenomena; resistance, e. m. f., heating, etc.

Corona, as a particular case of ionization and conduction in gases; study of the individual layers of ionized gas, from the electrode out; space charge, mobilities of ions, etc.

Dielectrics (topics discussed above).

Discharges; glow, brush, streamers, sparkover; their spectroscopy; character of ionization, numerical relationships.

Electromagnetic Theory; circuit equations, propagation of disturbances in dielectrics, dispersion; vector calculus operators; eddy currents in large conductors.

Electrometers; uses, theory, improvements in construction to facilitate setting up and use.

Electrons and Positive Ions; the fundamental properties: mass, charge, velocity, equivalence to a current, magnetic and electrostatic fields produced by such ions; action of external fields on an ion; relativity correction for mass; statistical mechanics of ions and neutral particles of matter in a mixture; reflection, ionization, diffusion, mobility, space charge; clustering; different kinds of collisions; refraction from crystals.

Fields, Electric and Magnetic; theory of fields, mapping out a field experimentally; theoretical plotting of lines of force and of equipotential surfaces; extension to three-dimensional problems.

Heat conduction in electric conductors and in dielectrics; accurate measurement of temperature distribution in electrical apparatus; theoretical investigation of heat flow in connection with iron loss and dielectric loss.

High-Voltage Tests; development of the technique of impressing a voltage of desired magnitude and wave form (steady, sinusoidal, impulse, etc.) and of accurately measuring its effect.

Inductance; measurement and theoretical computation of, for coils, lines, cables, and conductors of irregular shapes; effect of frequency.

Lichtenberg Figures; a detailed study of their production and properties; development of more sensitive figures which would clearly differentiate between the magnitude of an impressed voltage and its wave form.

Lightning Protection; development of laboratory tests for lightning arresters under conditions approximating actual service; measurement of actual line disturbances; production of materials and combinations with a smaller time lag, for lightning arresters; valve action; effect of a resistance in series with a protective device.

Measurements of amplification, current, frequency, voltage, power, phase angle, resistance, inductance, capacitance, time intervals, lengths, etc., when these quantities are extremely small, extremely large, of transient nature, or have to be observed under difficult conditions. Measurement of quantities introduced by the modern electronic physics, such as ionic currents, quanta, radiations, spectral lines, photoelectric effects, etc.

Oscillations; generation of electric oscillations; suitable circuits; theory of complex oscillations; the matrix theory of spectral lines.

Oscillographs; further development of types to extend the present range of usefulness.

Photoelectricity; theory of; measurement of the quantities involved; development of better photoelectric cells; new applications of such cells.

Piezoelectricity; theory, applications, apparatus, measurements.

Quantum Theory. This theory is the foundation of modern physics, and one not familiar with its premises and formulas is cut off from reading most modern books and periodicals in physics and from following the progress of the art.

Spark-Gaps and Sparkovers. Much remains to be done in ascertaining the behavior under various conditions of gas pressure, temperature, and moisture. A more rational theory, in terms of electronic ionization, photoelectric effect, and space charge is also needed.

Spectroscopy is proving to be a very powerful tool in various physical studies, so that it is of importance for engineers to become familiar with its methods, theory, and nomenclature, such as band and line spectra, arc and spark spectra, relative intensities of lines, superfine structure, terms, series, excitation by collisions and by radiations, etc.

Structure of Matter. The present knowledge of intra-atomic phenomena is in most cases insufficient to account for the complex phenomena with which engineers are concerned, making an empirical approach unavoidable. Nevertheless, a rapid progress is being made in atomic physics, and new methods and concepts are being introduced, such as quanta, relativity, the matrix theory, the wave mechanics (Broglie-Schroedinger), etc., so that engineers working on the border-line of physics should keep posted at least on the general trend of the progress, introducing new concepts and terminology into their work as much as possible.

Thermionics; emission of electrons from hot bodies; theory and methods of measurement.

Transient Phenomena; although the theory of many

transients has been thoroughly investigated, yet there are many others of greater complexity or of shorter duration, for which we have neither a satisfactory theory nor proper recording devices.

Vacuum Technique. More and more electrical measurements have to be performed in a high vacuum or under reduced pressure, and it is of importance to continue developing pumps, pressure gages, temperature and moisture control, elimination of impurities, etc., to make such measurements simpler and more accurate.

Waves and Surges along wires and in dielectrics acquire greater and greater importance both in power engineering and in communication work. Their experimental investigation is for the most part quite difficult, for they are transients in time and in space, whereas our recording devices are stationary and measure transients in time only. The theory of such transients is also quite involved and requires a knowledge of some new and advanced branches of mathematics and physics. Nevertheless, the electrical profession as a whole will have to develop experts capable of dealing with such problems, and a concerted effort should be made without further delay, possibly beginning with the best colleges of engineering.

Wave Mechanics. At the present writing, much of theoretical atomic physics is being re-written on the basis of the so-called "wave mechanics," introduced by de Broglie and Schroedinger. If this point of view continues to be successful, the next generation of engineers may have to deal with concepts entirely different from ours. Even such well-established principles as electronic orbits within an atom, begin to be looked upon as mere abstractions of the human mind rather than physical realities. For a general exposition of this theory see H. F. Biggs, "Wave Mechanics," *Oxford University Press*, 1927; K. K. Darrow, *The Bell System Technical Journal*, 1927, Vol. 6, p. 653; W. F. G. Swann, *Journal of Franklin Institute*, 1928, Vol. 205, pp. 323 and 519.

X-Rays. The importance of X-rays in various industries increases each year, so that many more electrical engineers should become familiar with the theory of these particular radiations, as well as with the handling of the apparatus and specimens. Moreover, X-rays are proving to be a powerful means of studying the structure of matter, and the constitution of the atom, particularly in its inner parts adjacent to the nucleus, which latter remains the least known part of the atom.

VLADIMIR KARAPETOFF, *Chairman.*

High-Frequency Measurements

ANNUAL REPORT OF THE COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

To the Board of Directors:

The Committee on Instruments and Measurements is at present studying several pertinent phases of electrical measurements through standing subcommittees as follows:

1. Measurements of Variable Power and Large Blocks of Energy
2. Dielectric Power Loss and Power-Factor Measurements
3. Measurement of Non-electrical Quantities by Electrical Means
4. High-Frequency Measurements
5. Remote Metering

The present status of these is as follows:

Variable Power and Large Blocks of Energy

This subject was covered in the report of the committee for 1925-26. Additional matter for future report is being collected by the subcommittee under the chairmanship of Mr. T. E. Penard.

Dielectric Power Loss and Power Factor

This subject was covered by symposium at the Niagara Falls Regional Meeting of the Northeastern District, May 1926. Additional matter is submitted in the following report by Mr. H. Koenig, subcommittee chairman.

In May 1926, a symposium on dielectric loss and power factor measurements was held at Niagara Falls. The symposium was called for the purpose of recording the then well-known methods of taking such measurements, probably as the first step toward standardizing such tests.

It is a difficult matter, of course, to determine just how effective the symposium was. It was the feeling of those who presented papers describing the various methods of making dielectric loss and power factor measurements that there was little hope of standardizing on any one method. The symposium did serve, however, to clear the atmosphere about these measurements and to point out the advantages and disadvantages of each method. It was also indicated at that time that a scheme for calibrating and checking the various methods now in use would be of great advantage.

Since the symposium, there have been two known advances in the line of checking dielectric loss equipments, particularly in the tests of underground cable. The first is the calorimeter method which was brought out in the discussion at the symposium by Mr. E. S. Lee of the General Electric Company. The second is the use of standard loads which have been developed at the Electrical Testing Laboratories. To the best of my knowledge, the only checking by the calorimeter method has been done by the General Electric Company in their own laboratories. A paper entitled *A Thermal Method of Standardizing Dielectric Power Loss Measuring Equipment*, by Messrs. J. A. Scott, H. W. Bousman, and R. R. Benedict, (A. I. E. E. Quarterly Trans., July 1928) was presented at the Baltimore Regional Meeting of the Middle Atlantic District, April 1928, describing further comparisons using this method.

During the spring of last year a set of standard loads developed at the Electrical Testing Laboratories was used in an intercheck covering ten cable factories in the eastern part of the country. The result of this intercomparison was very satisfactory. It is hoped that some time in the near future a paper covering the tests will be written.

All other developments have been along the line of improving the technique of making measurements rather than the introduction of new circuits or methods. Neither has there been any further effort along the lines of standardizing on the method of testing.

Numerous articles have been published in some of the foreign technical magazines covering dielectric loss and power factor measurements. No new methods have been suggested nor have radical changes been made in the methods in use in this country.

The importance of proper shielding in making dielectric power loss measurements is becoming more generally realized. A paper presented by C. L. Kasson at the Pittsfield Regional Meeting of the Northeastern District, May 1927, entitled *High-Voltage Measurements on Cables and Insulators*,[1] emphasized the necessity of proper shielding. The subcommittee is planning to hold a symposium on this subject in the spring of 1929 dealing with the general subject of shielding both in dielectric power loss and other measurements.

Non-Electrical Quantities by Electrical Means

This subject was reported in a paper by P. A. Borden published in the Transactions of the A. I. E. E., Vol. XLIV (1925), p. 238, together with an accompanying bibliography. The compilation of the bibliography has been continued by Mr. Borden, a second supplement having been published with the report of the Committee on Instruments and Measurements for

*COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:

Everett S. Lee, Chairman.

O. J. Bliss,	F. C. Holtz,	Wm. J. Mowbray,
P. A. Borden,	I. F. Kinnard,	T. E. Penard,
W. M. Bradshaw,	A. E. Knowlton,	R. T. Pierce,
H. B. Brooks,	H. C. Koenig,	E. J. Rutan,
A. L. Cook,	W. B. Kouwenhoven,	G. A. Sawin,
Melville Eastham,	E. S. Lee,	R. W. Sorensen,
W. N. Goodwin, Jr.,	E. B. Merriam,	H. M. Turner.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

1. A. I. E. E. Trans., Vol. XLVI, 1927, p. 635.

1926-27. A third supplement of the bibliography is attached to this report.

A study of the range of subjects in this bibliography shows the ever-increasing extension of the measurement of non-electrical quantities by electrical means. The number of the articles being published at present on this subject is too extensive for Mr. Borden to continue their compilation. Instead, a series of papers or lectures on the various subjects involved will be presented before the Institute. The lecture by Dr. C. A. Heiland on "Geophysical Methods of Prospecting" given at the Summer Convention, Denver 1928, is the first of this series.

High Frequency Measurements

This subject was thoroughly treated in a symposium at the Pittsfield Regional Meeting of the Northeastern District, May 1927, a résumé of which was given in the report of the Committee on Instruments and Measurements for 1926-27. Due to the wide interest in this subject and the rapid change in technique it was thought desirable to have a member act as liaison officer with the I. R. E. Committee on the Determination of Circuit Constants. The I. R. E. Committee has prepared a list of references containing the various types of measurement and in addition has developed new methods particularly with reference to the measurement of inductance of several hundred henries such as found in audio frequency transformers and choke coils both with and without superposed direct current. The report of this work is to be published. Professor H. M. Turner, subcommittee chairman, has been active in this work.

Remote Metering

The following report prepared by Mr. E. J. Rutan, subcommittee chairman, gives the results of answers to questionnaires relative to the present status of this subject.

The Instrument and Measurements Committee sent out questionnaires for the purpose of obtaining information on remote metering equipment now in use. These questionnaires were sent to a number of representative electric power companies, railroads, manufacturers, and public utility holding companies located both in this country and in Canada. From a total of 108 inquiries, 76 replies have been received as listed in Table I:

TABLE I

Group	Classification	Number of Replies
A	Electrical Transmission of Electrical Measurements	31
B	Electrical Transmission of Mechanical Measurements	10
C	Remote Metering Equipment in Use, no Data Given	3
D	Prospective Users of Remote Metering Equipment	6
E	No Remote Metering Equipment in Use	26
	Total	76

The purely electrical remote metering systems, as reported in the replies in group "A," can be classified into the ten distinct systems given in Table II.

TABLE II

Classification of Remote Metering Systems

1.	Voltage	6.	Potentiometer
2.	Impulse	7.	Frequency
3.	Position (induction)	8.	Impulse Condenser
4.	Inverse Current	9.	Contact Integration
5.	Current	10.	Thermal Converter

Referring to a paper on the *Automatic Transmission of Power Readings*, by B. H. Smith and R. T. Pierce, presented at the Midwinter Convention in Philadelphia, February 1924, it will be noted that the first seven types of systems listed in Table II were described in that paper. In the discussion that followed, the thermal converter type was also mentioned. The two systems not mentioned in the paper are not necessarily new. The contact integration system was mentioned in five replies and the impulse condenser was mentioned in two replies. Judging from the replies to the questionnaires, no new fundamental remote metering devices or systems have been developed since the presentation of the paper by Messrs. Smith and Pierce. The systems described in that paper will be given only a brief general description here but the other three systems will be described more in detail.

An attempt has been made to give an idea of the characteristics of operation and the accuracy of each method as it was reported. This was done in spite of the fact that nearly all of the users of remote metering equipment were compelled to report the performance of their systems under widely varying conditions. Certain systems whose inherent characteristics render them inaccurate due to interference from outside sources, can be made more reliable by the proper installation and shielding of the transmission line. It may also be noted that while the transmitter is often sufficiently accurate the receiver chosen to operate with it necessarily limits the accuracy of the system. This may cause the reported accuracy to be low, while a more accurate receiver would result in a more favorable reply. The importance of this point is evident when it is realized that many systems are classified according to the type of transmitter used without reference to the type of receiver. It is evident, then, that more definite information is needed to reconcile many of the apparently contradictory replies.

No attempt has been made to summarize the first cost and maintenance as no definite figures were given, and the replies received were evidently based upon the correspondent's limited knowledge of only a few of the systems in use.

1. Voltage. In this system the voltage supplied to the receiver is varied by a potentiometer which is operated by an instrument measuring the quantity desired. Some types are varied by a Kelvin balance or relay type graphic meter. The indications are trans-

mitted over supervising wires, pilot wires, or pressure wires to a voltmeter type indicating or graphic meter.

The chief advantage of this system is its simplicity. Obvious disadvantages are its sensitiveness to changes in line resistance and the necessity for close regulation of the supply voltage.

A few companies reported the reading of voltage directly over distances from a few hundred feet to two miles.

2. Impulse. This method seems limited to watthour type meters in which impulses proportional to the speed of the meter are sent out to receivers where polarized relays actuate an escapement. Dials geared to the escapement record the power being measured.

This method has the advantage of being positive in its action and quite independent of line conditions. The distance over which this system may be used seems to have no definite limit, the greatest reported distance being 200 miles. Some disadvantages are the intricate type of receiver necessary, a delicate transmitter which is likely to introduce errors, and the possibility of being affected by static disturbances. The reported accuracy seems to range from "fair" to plus or minus one per cent of full scale deflection.

3. Position. This method employs two similar a-c. induction motor units in which the rotor of the receiver closely follows the movements of the rotor of the transmitter.

This system is very simple and requires little or no attention. It is also very reliable, positive in action, and comparatively independent of line conditions. The line resistance limits the distance over which operation is possible, the limiting resistance being about 3000 ohms.

This method has the disadvantage of requiring five wires for operation. It is also reported that the transmitter needs a powerful operating torque, thus making it necessary to use more powerful instruments. It is sometimes necessary where a number of large receivers is connected together, to make use of power amplifying relays and motors.

The reported accuracy of this system as given by one manufacturer is two per cent of full scale deflection.

4. Inverse Current. This method makes use of a motor operated rheostat, controlled by the indicating or recording meter, which simultaneously adjusts the circuit resistance and the counter torque on the instrument. The receiver is a recording or indicating ammeter which receives current inversely proportional to the load.

An outstanding advantage of this method is the ease with which any number of indications may be totalized by connecting the rheostats of each meter in series. The resultant current is then inversely proportional to the total load.

The chief disadvantage lies in the complicated design and wiring necessary. The precision is also reported as being low or only fair.

5. Current Balance. This method is similar to the inverse current method except that the rheostat is connected to a Kelvin balance type of meter and the resultant current is directly proportional to the load. The receiver may be an inverted transmitter or an indicating or recording ammeter.

These instruments may be placed in parallel and the totalized current is then proportional to the total load. This method seems quite widely used, 9 replies reporting satisfactory operation of this system. One manufacturer reported 31 users of this system, 5 of whom replied to the questionnaire. Seven users of method reported transmission distances of at least 3 mi. and up to 24 mi.

The accuracy appears to be good, some stating that it depends on the choice of a receiver.

6. Potentiometer. The potentiometer type may also consist of a Kelvin balance type meter which controls a motor operated rheostat, but in this case it is the line voltage which is varied. The receiver may consist of motor operated rheostat controlled by a contact making voltmeter; or as reported in one letter, a milliammeter is used.

One of the advantages of this system is that the calibration is not materially affected by a change of line resistance. Another advantage is that a telephone line may be used for transmission. This method was reported in use on lines up to 56 mi. in length. The accuracy is reported as "fair" and probably depends on the choice of equipment.

7. Frequency. This is a complex system in which a Kelvin balance type of meter is made to control the frequency of a small a-c. generator. At the receiving end a frequency meter is used, calibrated to read load power. This system is easily adapted to totalize any number of readings. The control of apparatus may also be effected.

This system does not seem suitable for customer installation due to its complex nature, involving as it does elaborate apparatus and requiring constant attention. When used by a company that uses and distributes large blocks of power over considerable distances, the excellent results that are obtained would seem to warrant its installation.

8. Impulse Condenser. In this novel system, contacts on several meters are momentarily made to connect a condenser to a charging circuit, and the receiving instruments perform a measurement upon the rate of discharge of this condenser through a resistance. This system was used over lines 3½ mi. long.

The accuracy of this system seems to be low. The information received for this method is meager, but little seems to be said in its favor.

9. Contact Integration. This system may consist of contacts operated by a watthour meter, wherein the total number of contacts made over the system is totalized on a recording instrument, or the contacts made by demand meters are recorded at one point

on one instrument. The greatest reported distance of transmission was 5 mi., but this range may be extended by the use of suitable relays.

The accuracy of this method seems to depend upon the type of transmitters and receivers and the amount of local interference. Accuracies from one to two and one-half per cent were reported.

This system apparently gave satisfactory service in four out of five reported cases, while the fifth correspondent reported a failure due to induction from a nearby high-voltage line.

10. Thermal Converter. The important unit in this system is known as a thermal converter, and consists of two heating elements so connected to the instrument current and potential transformers that the temperature difference of the two elements is proportional to the watts in the metered circuit. Thermocouples are placed in this converter in such a manner that the "hot" junctions are associated with one heating element and the cold junctions with the other. The resultant thermoelectric potential is proportional to the difference in temperature of the two heating elements and is therefore porportional to the watts or power in the circuit. It was found possible to design the thermal converters to give a linear characteristic over the range used, and thus allow the units to be connected in series, when it is desired to totalize loads from a number of sources.

The accuracy of this method seems to lie in the receiver, which is usually a high-grade recording potentiometer, when accuracy may be of the order of one-half of one per cent. Thus a null method of measurement is used which practically eliminates any possible effect due to changes in line resistance. Indications have been transmitted successfully up to 8 mi. over telephone and supervisory lines. Other reported advantages are the lack of moving parts in the transmitting unit and the complete reversibility of the converters. This latter feature permits the use of this method on tie feeders where a reverse of power may occur.

This is the only new type of system developed since 1922 which has come to the attention of the committee. Arrangements are being made for the presentation of a description of this system before the Institute.

Conclusion

It is still the feeling of the subcommittee that sufficient operational data have not yet been submitted to allow conclusions to be drawn as to the accuracy of the remote metering systems in use.

Additional Subjects

In addition to the work being carried on by the standing subcommittees as reported above, there are several other subjects which the committee are working upon as the following:

System Disturbances

There is a growing demand for recording instruments for switchboard application to record the variation of current, voltage, and power with time during system disturbances. In this connection a symposium was held jointly by the Committee on Protective Devices and the Committee on Instruments and Measurements at the New Haven Regional Meeting of the North-eastern District, May 1928, at which time two series of papers were presented, one describing available instruments for making these measurements and the other giving the experiences of the operators in the use of these instruments. This symposium was under the direction of Mr. R. T. Pierce for the Committee on Instruments and Measurements. The papers presented under the auspices of this committee were:

Hall High-Speed Recorder, by C. I. Hall*

Pages from the Hall High-Speed Recorder, by E. M. Tingley†

Oscillograph Recording of Transmission Line Disturbances, by J. W. Legg†

High-Speed Graphic Voltmeter, by A. F. Hamdi and H. D. Braley.*

Revision of Electrical Units

Following the presentation by Dr. E. C. Crittenden at the Summer Convention of the Institute, Detroit, 1927, of a paper entitled *The International Electrical Units*, a resolution was presented and passed that the matter of the revision of the electrical units should be referred to the Committee on Instruments and Measurements for their consideration and study. This has been done and resolutions have been prepared and transmitted to the Board of Directors through the Standards Committee, urging the United States Bureau of Standards and other foreign national standardizing laboratories to undertake the necessary researches to eliminate the present discrepancies between the legally established electrical units and the absolute units which they were intended to represent, and to urge the legalization of absolute units.

Measurement of Core Losses in Terms of Sine-Wave Core Losses

The Committee on Instruments and Measurements has been asked to investigate and report on the best way to make core loss measurements so that they will give accurate sine-wave core losses regardless of the wave form employed for excitation. This subject is being studied by a working committee under the chairmanship of Mr. W. M. Bradshaw.

Distortion Factor—Definition and Method of Measurement

The Committee on Instruments and Measurements has been asked to give consideration to the adoption of a definition for distortion factor and methods of test, as disclosed in a report of the French Electro-technical Commission entitled "Methods of Determining the Distortion of the Voltage Wave of Alter-

*A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928.

†A. I. E. E. Quarterly Trans., Vol. 47, No. 4, Oct. 1928.

nators." This matter is being considered by a working committee under the chairmanship of Mr. W. M. Bradshaw.

ACKNOWLEDGMENT

It is but fitting that we recall at this time the contribution in the past to the work and activities of this committee by Mr. J. R. Craighead. Mr. Craighead was appointed Chairman of the Instruments and Measurements Committee at the beginning of this year but he was removed from us by sudden death November 22, 1927. In his passing there have been lost to us the contributions of an active and energetic worker, and the advice and counsel of a scholar.

EVERETT S. LEE, *Chairman.*

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MEASUREMENT OF NON-ELECTRICAL QUANTITIES BY ELECTRICAL MEANS

Note: The first supplement of this Bibliography is published in the TRANSACTIONS of the A. I. E. E., Vol. XLIV, 1925, p. 238.

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The third supplement is given herewith.

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Electrical Communication

ANNUAL REPORT OF COMMITTEE ON COMMUNICATION*

To the Board of Directors:

The Committee on Communication submits the following report as a summary of the progress which has been made in the electrical communication art during the past year.

Printing Telegraphs

There has been continued growth in the use of printing telegraph instruments. In addition to the applications for police service mentioned under another heading, the volume of commercial message and similar traffic handled by such instruments shows a steady gain, both on long and short circuits. As an example of the latter, it may be noted that more than 800 circuits connecting main and branch officers of the telegraph companies are now equipped with printers.

The tendency to reduce manual operations as much as practicable has been quite pronounced in ocean cable telegraphy during recent years. As a result, printing telegraph equipment is now employed on both long and short cables in many cases. Recent developments in this direction were described in a paper entitled *Printing Telegraphs on Ocean Cables* which was presented by H. Angel at the 1927 Summer Convention of the Institute.

The automatic tape transmission system for telegraph tickers which was mentioned in the 1926 and 1927 reports has been further extended during the past year, so that full market quotations are now available to practically all sections of the United States.

Telegraph Repeaters

Many of the repeaters now used on long telegraph circuits, both in land line and ocean cable service, are of the regenerative class. In such repeaters, automatic means are employed to retransmit practically perfect signals although the received signals may be so badly distorted that with earlier forms of repeaters the retransmission would be far from perfect. A description of one type of regenerative repeater and an outline of operating experience with it was given in A. F. Connery's paper on *A Non-Rotary Regenerative Telegraph Repeater* presented at the 1927 Summer Convention.

Rather important advances have been made in the simplification of circuit and equipment arrangements for telegraph repeaters installed in central telegraph offices.

Telegraph Transmission Theory

A paper entitled, *Certain Topics in Telegraph Transmission Theory* was presented at the Winter Convention of the Institute by H. Nyquist. In addition to presenting a quantitative statement of certain fundamental telegraph requirements, this paper presented for the first time an analysis of the fundamental problems involved in single sideband carrier telegraph transmission which may offer important economies in frequency range under some conditions.

Cord Carriers for Telegrams

For some years past, most large telegraph offices have been equipped with mechanical conveyors, usually of the moving belt class, for the transfer of telegrams from one part of the operating room to another. A multiple cord carrier system has recently been developed which is proving very satisfactory for such conveying service. Where delivery to two or more points is necessary, the cord carrier equipment costs much less than the equivalent flat belt equipment. The power required to operate a three-channel cord system is no greater than that needed by a single-channel flat belt. Other advantages of the cord equipment are increased speed, reduced maintenance expense, minimum interference with lighting, and complete visibility at all points, thus facilitating inspection.

Dial Telephony

The rapid application of dial telephone systems has continued. During the year, about 500,000 dial telephone stations were installed, bringing the total in service in this country, as of the first of January 1928, to approximately 2,900,000 stations or about 16 per cent of the total telephones in service.

A paper entitled *Some Recent Developments in Dial Systems,* by W. E. Farnham and H. M. Bascom, was presented at the Student Branch Convention and Sectional Meeting in New York in April of this year.

The dial system of operation has been extended to service from one suburban point to another suburb of the same city. This matter was discussed in a paper entitled, *Tandem System of Handling Toll Calls in and About Los Angeles,* by E. Jacobsen and F. D. Wheelock, which was presented at the 1927 Pacific Coast Convention.

Toll Telephone Service

During the year, telephone toll service was established between the United States and a number of important cities in Mexico, including Mexico City, Tampico,

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*COMMITTEE ON COMMUNICATION:

H. W. Drake, Chairman,

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H. P. Charlesworth,	Erich Hausmann	Chester W. Rice,
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L. W. Chubb,	F. H. Kroger,	J. K. Roosevelt,
J. L. Clarke,	R. H. Manson,	H. A. Shepard,
C. E. Davies,	R. D. Parker,	J. F. Skirrow,
R. D. Evans,	S. R. Parker,	H. M. Turner,
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D. H. Gage,		F. A. Wolff.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Monterey, Saltillo, San Luis Potosi, Puebla, and others. The service was inaugurated by an exchange of greetings between President Coolidge and President Calles at the capital cities of the two republics over a circuit 3360 mi. long. The service from Mexican points was further extended to points in Canada by the end of 1927.

The various connections of the United States telephone network to important cities in Canada were augmented during the year by the completion of a circuit from Bismarck, North Dakota, to Regina, the capital of Saskatchewan.

A substantial improvement was made in the handling of toll calls, especially by increasing the percentage which are handled while the subscriber remains at the telephone.

Telephone Toll Cables

The extension of the network of toll telephone cables throughout the country continued at an increased rate during the year 1927, about 2000 mi. of cable being installed. Important additions included the completion of a route from Albany to Cleveland through Syracuse, Rochester, and Buffalo; the extension of the cable south of Washington to Petersburg, Virginia; and an extension from Chicago to Terre Haute, Indiana. In addition, a toll cable between Buffalo and Hamilton is approaching completion and another between Toronto and Oshawa is being started. This supplements the existing Toronto-Hamilton cable and provides a connection between the toll cable system in Canada and the great system in the United States.

At the present time, 7,500,000 telephones of the Bell System have direct access to the toll cable network in the northern and eastern parts of the country which provides within that area toll service which is relatively immune from the effects of storms.

Planning Extensions to Telephone Plant

The problems involved in the planning of telephone plant and descriptions of the telephone plant in various regions were discussed in a number of papers presented at Institute meetings. The principal papers were as follows: *Advance Planning of the Telephone Toll Plant,* by J. N. Chamberlain, presented at the Pacific Coast Convention; *Telephone Toll Plant in the Chicago Region,* by Burke Smith and G. B. West, presented at the Chicago Regional Convention; and *Planning Telephone Exchange Plants,* by W. B. Stephenson, presented at the St. Louis Regional Meeting.

Communication Apparatus and Materials

The application of permalloy to communication problems continued during the year. Interesting information regarding this material was given in a paper entitled, *Manufacture and Magnetic Properties of Compressed Powdered Permalloy,* by W. J. Shackleton and I. G. Barber, which was presented at the Winter Convention.

A paper entitled, *Recent Developments in the Process of Manufacturing Lead-Covered Telephone Cable,* by C. D. Hart, was presented at the Chicago Regional Meeting.

Electrical Transmission of Pictures

While no new stations have been added to the telephotography network of the Bell System (Boston, New York, Atlanta, Cleveland, St. Louis, San Francisco, and Los Angeles), interest in the service is increasing greatly and it is becoming much more important to the press.

Television

At the last annual meeting in New York a talk on television was given by Dr. H. E. Ives, followed by a demonstration at the Bell Telephone Laboratories. A symposium on television at the Detroit Summer Convention was led by Dr. Ives and also was followed by demonstrations. The symposium included notable papers entitled: *The Production and Utilization of Television Signals,* by F. Gray, J. W. Horton, and R. C. Mathes; *Synchronization of Television,* by H. M. Stoller and E. R. Morton; *Wire Transmission of Television,* by D. K. Gannett and E. I. Green, and *Radio Transmission of Television,* by E. L. Nelson.

Carrier-Current and Superimposed Systems

During the year there was a marked increase in the use of carrier-current systems in commercial telephone and telegraph plant, including a new system of a simplified nature which provides a single channel and is applicable economically to distances as short as 75 mi. The total length of carrier telephone circuits added during the year was approximately 65,000 channel mi.

In the application of carrier telegraph arrangements over 125,000 two-way channel miles were added to the Bell System during the year. This includes channels obtained from open-wire facilities by carrier frequencies above the voice range as well as voice-frequency carrier telegraph channels obtained from circuits in long toll cables. The increase is approximately evenly divided between the two types.

The application of carrier-current telephony to communication over power lines has increased steadily until, at the present time, there are in this country alone, 298 fixed stations in operation. Recent improvements in these systems have been along the lines of interconnecting them with private telephone systems. Portable and semi-portable carrier communication apparatus is being successfully used in conjunction with fixed stations. The large majority of these installations provide duplex operation, each system on a single frequency. The transmitter output is in the order of 50 watts, in the majority of the fixed installations; this power is proving adequate for usual conditions. As the demands for increased channels are made, the need of reducing the width of the communication channel without sacrificing understandability becomes more imperative.

Utilization of carrier current for other than communication purposes is rapidly increasing. The appli-

cations are for control of street lights, pilot protection of transmission circuits, supervisory control of substations and similar equipment, telemetering, etc.

Certain power companies are now using devices to operate graphic indicating meters at a distance, by means of d-c. impulses carried over signal circuits. By this arrangement, an operating supervisor or system operator may see at any moment the amount of power that is being fed into the system from generating points located at various places in the area covered by the power system. The total load taken by a town or city at some point may also be recorded at the system operating center.

Some recent developments in carrier current and other superimposed systems were described in the following papers presented at Institute meetings during the year:

The Use of High Frequency Currents for Control, by C. A. Boddie, Summer Convention 1927.

A Carrier-Current Pilot System of Transmission Line Protection, by A. S. Fitzgerald, Pacific Coast Convention 1927.

Coupling Capacitors for Carrier-Current Applications, by T. A. E. Belt, Pacific Coast Convention, 1927.

Supervisory Control Apparatus

In the power field, elaborate supervisory and control arrangements are now available by which an operator can control switches or other apparatus at distant points, and by means of currents transmitted back from the distant point determine the conditions which exist there. The Westinghouse Company reports that development work is being started on a form of such supervisory control apparatus, which is of interest in the communication field as it is intended to operate at frequencies in the voice range which can be transmitted over telephone circuits. The work has not yet reached the point where the possibilities and limitations of the system can be determined. Demonstrations of a preliminary model of the apparatus under the name "Televox" have, however, created considerable popular interest from the fact that the operation of such an arrangement over telephone circuits can be thought of as simulating conversation between persons.

Transatlantic Radio Telephony

The opening of transatlantic telephone service between the United States and England was covered in last year's report. The service was improved by the completion of a radio receiving station at Cupar, Scotland, which is located as far north as conveniently possible for the purpose of reducing interference caused by atmospheric disturbances.

The time during which service normally is available has now been extended to 14½ hr., the period of service extending from 5.30 a. m. to 8.00 p. m., eastern standard time. The service was extended to Cuba and to five cities in Canada as well as to various cities of Continental Europe.

The outstanding event which took place during the period covered by this report was the holding of a joint meeting of two organizations on opposite sides of the Atlantic for the first time in history. This was a joint meeting of the Institute during the Winter Convention in New York with the British Institution of Electrical Engineers in London.

Preliminary to the joint session, a paper entitled, *Transatlantic Telephony—The Technical Problem,* was presented by O. B. Blackwell, and a paper entitled, *Transatlantic Telephony—The Operating Problem,* was presented by K. W. Waterson.

The joint session was preceded by the opening of communication from New York by Mr. Charlesworth who spoke to Colonel Lee in London. The telephone was then turned over to President Gherardi and to President Page of the British Institution of Electrical Engineers. After an exchange of greetings, brief addresses were given by Dr. F. B. Jewett and General John J. Carty from this side of the water and by Colonel Purves and Sir Oliver Lodge from London.

At various times during the year the transatlantic telephone service was discussed at a number of sectional meetings.

International Radio Conference

The International Radio-Telegraph Conference held in Washington in 1927 achieved several very important agreements affecting international radio communication. The delegates were faced with the responsibility of expanding an agreement made several years ago, mainly with a view to facilitating the use of radio in marine communication service. Since that agreement had been written, the use of radio had expanded to telephone as well as telegraph service and the field had widened to embrace in addition to the marine communication services, aids to navigation such as compass and beacon, aircraft and other new mobile services, point-to-point services, amateur and experimental work, and broadcasting. The new agreement had to apply to this much wider field of use without hampering the progress and development of the art. The most important achievements were the following:

The agreement on the assignment of frequency bands for services in the whole radio spectrum.

The recognition of the fact that every type or method of transmission of necessity occupies a definite frequency band or channel.

The agreement that interference to other services is the controlling limitation put upon the method of using a frequency channel.

The recognition of the amateur status in the international communication field.

The progressive suppression of the use of damped waves. No new installations using damped waves may be set up for land and fixed stations and the use of such

waves at existing stations is forbidden after January 1, 1935. On ship and aircraft stations, new damped wave installations may be made only if such apparatus uses less than 300 watts on full power, and the operation of these damped wave installations is forbidden after January 1, 1940. Thus in 12 years the history of damped waves will close.

The agreement upon the use of an automatic alarm signal in the marine service.

The setting up of an International Technical Consulting Committee.

Radio Broadcasting

Comparisons of results obtained by operating a broadcasting station with power outputs up to 100 kw. have established, fairly definitely, the essentials of this important subject.

Of considerable importance in connection with the performance of a high-power broadcasting station is the choice of site. Some locations are appreciably better than others, which indicates need of careful investigations before choosing a site.

Utilizing high-power tubes which recently became available, a 100-kw. transmitter has been developed which combines the essentials of all modern practises.

Since the previous report of this committee was made, two commercial 50-kw. broadcasting stations have been placed in operation.

Short-wave broadcasting and re-broadcasting in the U. S. and foreign countries has developed gradually with considerable recent improvements. These are mainly due to the utilization of sufficient power to provide dependable service and to improvements in the reception of short waves which have been almost exclusively used for this purpose.

Recent demonstrations of transmissions and receptions of both still pictures (facsimile) and moving objects (television), utilizing broadcasting transmitters, have indicated the probable future extensive application of these features to the present broadcasting service.

Other Radio Communication

During 1927 short wavelengths were first utilized to provide a commercial service designed to maintain contact between the home office and ships making around-the-world tours. Such a service was applied also to ships plying between the United States and the far East where the distances are very great.

The percentage of long distance communication handled by short waves increased further during 1927. In the United States there were installed on several long distance radio circuits, the Radio Corporation of America's projector system. This system has been in use a sufficiently long period to demonstrate that it is a large factor in making it possible to obtain an economical long distance radio communication service. This projector system includes not only directive transmission but also directive reception. The directive reception differs from the transmission in that several receiving antennas directive in themselves, are spaced in such a manner as to eliminate the momentary fading which previously had so limited the use of short waves. With this method of receiving short waves it is possible to obtain a record so free from mutilation as to be practically perfect. Thus, in a way not anticipated some years ago, there has been accomplished the elimination of the effect of static.

The development and application of radio transmissions to aid in guiding aircraft has made rapid progress during the year.

Railroad train radio telephone equipment has been developed for front-to-rear communication on long freight trains. The apparatus provides telephonic communication and call signals between the locomotive and the caboose under all conditions whether the train is standing or in motion, and even when the train is broken if the separation does not exceed four or five miles. A four months test of the equipment was recently successfully completed on the James River Division of the Chesapeake and Ohio Railroad.

For cases in which the expense of the above mentioned telephone system cannot be justified, a signal system of lower power has been developed for service between front and rear of long freight trains. It provides only for call signals and telephonic communication is not possible. In operation a cord similar to a whistle cord is pulled, and a loud high-pitched signal is produced at the opposite end of the train. The range of this system is not over four miles.

Radio telephone equipment for railroad hump-yard service has been developed to facilitate the classification of freight cars at congested terminal points. The apparatus is similar to the train radio-telephone equipment, except that it is of lower power. The apparatus provides one way telephonic communication between the yard-master's office and any locomotive in the yards. The apparatus is operated the same as any telephone, and its range is limited to about two miles.

Sound Reproduction

Improvements were made in the design of loudspeakers as regards efficiency, power, and uniformity over the speech frequency range. Some of the advances in design by which these improvements have been obtained were discussed in a paper entitled, *Loud Speakers of High Efficiency and Load Capacity*, by C. R. Hanna, presented at the Winter Convention, (A. I. E. E. Quarterly TRANS., Vol. 47, April 1928) and in a paper entitled, "A High Efficiency Receiver for a Horn-Type Loudspeaker of Large Power Capacity," by E. C. Wente and A. L. Thuras which was published in the *Bell System Technical Journal* for January 1928.

A paper entitled, *Electrical Reproduction from Phonograph Records*, by E. W. Kellogg, presented at the Detroit Summer Convention, discussed some interesting

mechanical and electrical problems encountered in the development of improved reproducing devices.

Fire and Police Signal Systems

Further refinements of apparatus have been introduced in fire alarm systems during the past year. Improved automatic repeaters have recently come into use, the operation of which closely accords with the rules of the National Fire Protection Association requiring complete non-interference between coincidental signals, so that succession devices in street boxes will function, whether the boxes are on the same or on different circuits of the system.

In a new type of puncturing register the paper punchings are folded under instead of being detached, thus eliminating much objectionable paper dust; the instrument requires less power for its operation and runs at a higher speed than earlier registers.

Another improvement is the use of radio for communicating from fire alarm headquarters to moving apparatus, such as fire chiefs automobiles or fire boats. Boston has had such a broadcasting station for the past two years. It operates on a short wave, and has been found highly effective in sending orders to fire boats when absent from their regular berths. New York has recently experimented with a similar system.

In police signaling, an important development is the increasing use of telautographs and telegraph printers for interstation communication. These systems have been found useful in quickly and accurately spreading the news of hold-ups, automobile thefts, and other crimes. They have been found especially valuable where used in connection with the flashlight system of calling the patrolmen to the street signal boxes. A rather extensive installation of printing telegraph instruments made during the past year for the New York Police Department illustrates the expansion of service of this character. This system is so arranged that an operator at headquarters may send signals from a keyboard to any one precinct, to any group, or simultaneously to all precincts, the messages being printed automatically in page form at receiving machines placed close to the desks of officers in charge of precincts. Facilities are provided so that the receipt of the message may be acknowledged by each station. Another interesting system of this kind is in Connecticut, where police headquarters in twelve important cities are interconnected by telegraph printer circuits. It is expected that by the end of 1928 the system will be so extended that practically all of the cities in the state will be covered.

Several conflicting tendencies are noted in traffic signaling, particularly with respect to the colored lights or equivalent devices employed. While the green-amber-red cycle of signals has been adopted by many cities, others have favored either more or less complex arrangements. Centralized control of the street signals is being extended and while difficulties are experienced in so synchronizing operations as to minimize hazards and delays, it seems likely that this problem will ultimately be solved.

The blinker signals for outlying locations or crossings where there is little congestion are quite effective, particularly when equipped with Fresnel lenses. The gas type of blinker signal, using a tank of compressed gas for supplying the light jet has been superseded in many cases where electricity is available by a type using electric lamps.

H. W. Drake,
Chairman.

Production and Application of Light

ANNUAL REPORT OF THE COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

To the Board of Directors:

INTRODUCTORY

The following report of the Committee on Production and Application of Light, as on former occasions, consists chiefly of a résumé of the more notable achievements of the year in the art of lighting by electricity. It has been compiled from information supplied by members of the committee and by other authorities in their respective fields who have kindly cooperated with the committee.†

Production of Light

Most developments during the past year in the production of light have taken the form of refinements of design and adaptations of existing types of illuminants rather than of radically new methods or principles of light production.

INCANDESCENT FILAMENT LAMPS

Small Multiple Lamps. Within the past year a new and smaller 10-watt tungsten filament lamp for 110-, 115-, or 120-volt service has been placed upon the market. This lamp has a bulb 1⅜ in. in diameter, designated "S-11" and a new base termed "intermediate," which is approximately ⅝ in. in diameter and ¾ in. long, standing in dimensions between the medium screw base and the candelabra base. This is a new size in the group of multiple lamps. It has been developed for places where physical limitations make the use of lamps of previously existing standard types difficult or impracticable. It is designed to yield an average life of 1500 hr. at a rated efficiency of 7.85 lumens per watt. It is available in coated bulbs in any of seven colors, the coatings being of a nature to withstand outdoor service. This lamp is expected to find wide use, especially in electric signs of the smaller sizes, in the design of which it has been difficult to achieve artistic effects with lamps of larger physical dimensions. Other uses to which the new lamp lends itself are outdoor decoration as of Christmas trees and illumination of small lighted ornaments which have recently appeared on the market for interior home decoration. It may also find application in the extension of cove lighting to residences where it has been extremely difficult to adapt this method of illumination due to the physical dimensions of the lamps heretofore available.

Another new lamp employing the intermediate base has recently been developed and placed upon the market in a bulb designated C9-¼. This lamp is rated at 10 watts, 115 volts and is designed to yield an average life of 600 hr. at a rated efficiency of 8.95 lumens per watt. It is intended primarily for lighting of Christmas trees and is available in coated bulbs in any of seven colors. Fig. 1 shows the two new intermediate base lamps in comparison with the 10-watt S14 medium screw base sign lamp.

In addition to these new lamps employing the intermediate base, the 15-watt flame shape bulb decorative lamp for 110-, 115-, and 120-volt service, formerly fitted with candelabra base is now available also with intermediate base.

A complete line of sockets and adapters for intermediate base lamps is now upon the market, as well as strings of seven sockets wired in multiple for Christmas tree and other decorative lighting.

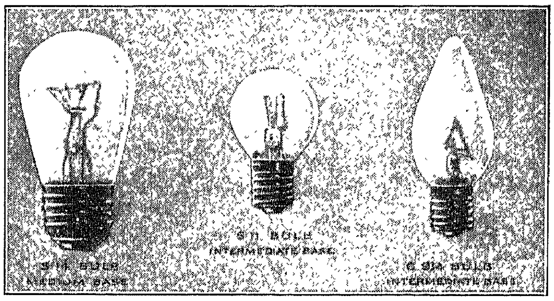

FIG. 1—10-WATT MULTIPLE LAMPS

Very Large Lamps. The successful production of incandescent lamps in sizes up to the 10-kw. lamp marks a distinct advance in the art of lamp manufacture and prepares the way for even larger sizes if they shall be needed. These extremely large lamps are manufactured for special purposes such as the lighting of aviation fields and motion picture studios. These applications are still in the developmental stage, though many installations are functioning satisfactorily.

Projection Lamps. A new development in the manufacture of incandescent lamps of the smaller sizes for projection purposes is the use of the "coiled-coil" filament by means of which the over-all dimensions of the light source are materially reduced, an object which is much sought in light projection. The resulting increase in uniformity and intensity of screen illumination has been a considerable factor in the growing popularity of home motion picture projection.

In certain types of concentrated filament lamps for

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J. R. Cravath,	H. H. Higbie,	B. E. Shackelford,
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	George S. Merrill,	

†See list of non-member contributors on page 12.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

light projection, more accurate and automatic positioning of the filament is attained through the use of a prefocused base consisting of a separate sleeve attached to an unthreaded base shell after the lamp has been otherwise finished.

The over-all dimensions of filaments of 750- and 1000-watt lamps for general service have been reduced in the interest of improved accuracy of light projection in flood lighting and of better distribution in the case of high-mounted industrial reflectors.

Street Railway Lamps. Two new lamps in inside frosted bulbs have been made available during the past year for street railway service. One of these is a 36-watt vacuum type coiled filament lamp designed for operation five in series on circuits of from 525 to 650 volts. The other is a low voltage, gas-filled lamp designed for operation at 30 volts per lamp, with approximately 20 lamps in series on the street railway circuit. This lamp has a special device incorporated in the lead-in wires by means of which the circuit is re-established in case of the failure of the lamp filament. Being designed for low voltage operation, it has a relatively short and heavy filament and is therefore relatively sturdy; being of the gas-filled type and having a comparatively heavy filament, its light output per watt consumption is 40 to 50 per cent greater than that of the clear bulb, straight filament, vacuum type lamp designed for like service.

New Large Bases. In order to strengthen the attachment of the base to the bulb in the case of certain of the very large sizes of lamps, a Mogul screw base has been developed which, in addition to the cemented joint, has a mechanical clamp around the neck of the bulb.

For heavy current lamps taking more than 25 amperes and operating in the base down position, there has been standardized a two-prong base which is designed to overcome heating difficulties due to current density and contact resistance experienced with former types of bases.

Short Circuiting Device. To extinguish the arc which may be formed upon the failure of the filament in the smaller street series lamps and to maintain a closed series circuit, the lead-in wires have been brought into close proximity for a certain distance. If the arc travels along the lead wires the globules of metal on the ends of the two wires unite and short circuit the arc before it has an opportunity to damage the base of the lamp and the socket.

Carbon Lamps. Though the use of carbon filament lamps shows a decrease each year, the numbers of these lamps which are still in service and the numbers which are sold each year are very large. Carbon lamps seem to be particularly popular in colored bulbs and in bulbs of special decorative or novelty types. For purposes of illumination their use is, of course, uneconomical, but for decorative use they appear to meet a certain small demand.

Operating Voltages. The standardization of lighting circuit voltages continues to show progress from year to year. It is estimated by the lamp manufacturers that at the present time in this country 94 per cent of the population within reach of electric service is in territories served by some one standard voltage (110, 115, or 120) and that more than 99 per cent is within territories served by one or more than one standard voltage, leaving only a fraction of one per cent distributed among the odd voltages between 100 and 130. The voltage used most generally is 115. It is estimated that 59 per cent of the population within reach of electric service is provided with electricity at this voltage.

Searchlights

The trend of development of military searchlight design since the war has been toward greater beam candlepower, lighter weight, greater mobility, and improved methods of control. There were two important developments in 1927.

One of these was the incorporation in the searchlight unit of a comparator system which makes it possible for the searchlight to be guided from a distance by accurate data transmitted electrically from a sound-locator station to the searchlight station. In anti-aircraft defense the pointing of the searchlight at the target is thus greatly facilitated.

The other development was the successful production of a 60-in. mobile searchlight unit employing a 250-ampere high intensity arc operated by a 25-kw. generating unit, and developing 1,385,000,000 maximum beam candlepower.

In order to facilitate signaling, searchlights of the smaller sizes in the Navy are being adapted to the employment of the incandescent lamp. Similar signaling searchlights using 1000-watt projection lamps have unique advantages in the submarine service in that the pressure on the projection drum may be equalized by allowing water to enter the unit.

Gaseous Conductor Lamps

Sign Types. The neon tube lamp for display and sign service has grown in popularity during the last few years. By the use of various mixtures of gases and also by the employment of fluorescent glass tubing a number of color effects is obtainable, though some of these are not entirely stable at the lowest temperatures attained in the northern part of the United States. These signs require for operation a relatively high voltage and are characterized by a low power factor (usually below 50 per cent) when supplied with alternating current. On the other hand the efficiency of light production of the orange-red neon tube sign is relatively high and the guaranteed service life is long.

The vivid color contrast with daylight offered by neon tube signs tends to promote their use in daytime as well as at night.

Hot Cathode Lamps. The hot cathode neon lamp, a very recent development in this field, consists of a glass

tube similar in form to that of the mercury vapor lamp now in general use, but filled with neon gas. The discharge through the gas is started and facilitated by the heating of the cathode. By this means the voltage drop at the electrode is reduced from 250 to 30 volts, making possible the operation of the lamp directly on a 115-volt a-c. or d-c. circuit. In this lamp the absence of electrode disintegration permits the passage through the tube of a comparatively large current with a resultant high intrinsic brilliancy and candlepower. It has been tried with some success in the illumination of opal letter signs, in the marking of pier heads and aviation fields and, in the form of a close spiral mounted at the focus of a parabolic reflector, as an airway beacon. It may be noted that this new form of neon lamp may be used in combination with the mercury vapor lamp to produce with high efficiency, light which is apparently white in color and which is expected to find application in color and panchromatic photography.

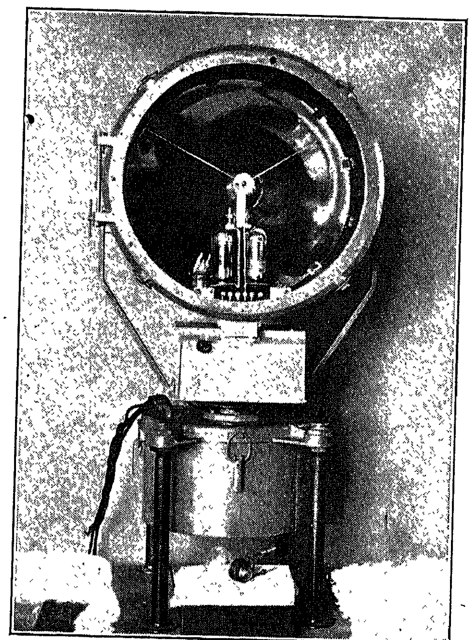

FIG. 2—NEON INDUCTION BEACON

Negative Glow Lamps. The negative glow socket type neon lamp (known as the G10 indicator lamp) which was mentioned in the 1926 report of this committee has undergone further development during the past year. The present form of this lamp is designed for operation on 115-volt a-c. circuits. It consumes about one-third of a watt and emits somewhat less than one-tenth of a candlepower. Its field of use is primarily that of an indicator or night lamp. The corresponding lamp for d-c. service is under development but is not yet available.

Television Lamp. A prominent position in the recent successful demonstrations of television has been occupied by a neon lamp of a type specially designed for that class of service. The neon lamp is uniquely adapted to that purpose by virtue of its instantaneous response to variations of voltage.

Induction Lamp. The electrodeless discharge in neon, in the form of the induction lamp has recently been employed experimentally as a light source for airway beacons. The bulb enclosing the luminous gas is of clear fused quartz about 1½ in. in diameter and is mounted at the focus of a searchlight reflector. A short wave pliotron oscillator mounted in the reflector housing generates the high frequency current necessary to excite the gas within the bulb. Due to its orange-red color the neon induction beacon illustrated in Fig. 2 is said to excel in visibility at a distance in both clear and foggy weather when compared with other sources of equal beam candle-power.

APPLICATION OF LIGHT

Interior Illumination

INDUSTRIAL LIGHTING

The year has witnessed advances both as to the general standards of industrial lighting and the extent to which modern methods are employed.

The industrial activities referred to in last year's report have undoubtedly secured a wider recognition of the value of good illumination in promoting workers' welfare and safety as well as speedy and economical production.

A survey of a considerable number of industrial plants on the lines of one of the largest electric service companies showed that on the average the electrical energy consumed for lighting approximately equaled that used for power purposes. Since this lighting service company has been particularly active for over a decade in promoting industrial lighting, the lighting of these plants is presumably better than would be found in most cities. But even allowing for this, the results indicate a more intensive use of light than would generally have been expected.

The Department of Labor and Industry, State of Pennsylvania, has adopted regulations for emergency lighting of places of public assembly and places where persons work after darkness. The rules call for an emergency illumination of at least half a foot-candle on the floor at exit doors, hallways, etc., leading to outside building exits, and of at least a quarter foot-candle on the floors of auditoriums. Control of the supply must function without dependence upon manual operation. The source of energy must be separate from that of the main lighting system, and when secured from outside the building must be supplied by two generating stations, an approved automatic throw-over switch being required.

COMMERCIAL LIGHTING

Though the past year has been marked by no outstanding development in commercial lighting practise, it has seen a more widespread application of illumination due to a better appreciation of its utilitarian and advertising value. While the present practise in the majority of stores and offices is to provide general illumination with diffusing glass enclosing globes, there

is a growing demand for lighting equipment of the semi-indirect type. In the main corridors of the newest office buildings and in hotel lobbies unique luminaires designed along the lines of modernistic art have appeared. These innovations in design not only provide an interesting variation but it is thought that they may lead to radical changes in types of commercial lighting equipment.

In the lighting of window displays the tendency has been to advance to higher intensities as the level of street illumination has risen and as the number and brilliance of electric signs have increased. The use of colored lighting and the employment of spotlights to create striking contrasts have been practised extensively during the past few years.

The more general use of color matching units is notable. Unfortunately such applications are peculiarly liable to misunderstanding and misrepresentation, both of which have been present to no small degree. Practise in artificial daylighting is in need of clarification.

Residence Lighting

The Modernistic Trend in Lighting Equipment. For several years European artists and designers, notably the French, have been striving to develop a style which will express twentieth century tendencies. Their work has influenced furnishings of all kinds, including lighting fixtures. These modernistic fixtures usually employ plane rather than curved surfaces and strong, pronounced lines. Color is used to advantage and there is remarkable absence of unnecessary applied decorative bits. Almost without exception exposed bare lamps find no place in this equipment. The lamps are generally hidden from view, the light being diffused by some external medium.

The modernistic movement is beginning to find its way into American homes and it is to be anticipated that it will have considerable effect on home lighting practise. Already a number of progressive American manufacturers is showing some excellent fixtures in this new spirit. Two wall units and a unique table lamp of domestic manufacture are illustrated in Fig. 3.

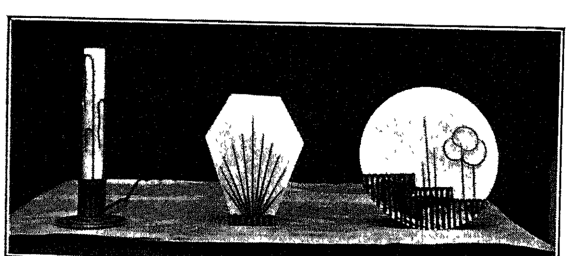

Fig. 3—Luminaires in the Modernistic Spirit

Use of Light for Ornament. Mention was made in last year's report of the development abroad of artistically lighted pieces of decoration. These lighted ornaments in general furnish no useful illumination, but give touches of high light in color about a room. They have been very aptly termed "the jewelry of the lighting installation." In the past year a great number of these devices has been imported and sold by the leading shops here. The tremendous potential field in America, however, cannot be covered by importations, and one of the leading American manufacturers has placed on the market a line of such ornaments, several of which are shown in Fig. 4.

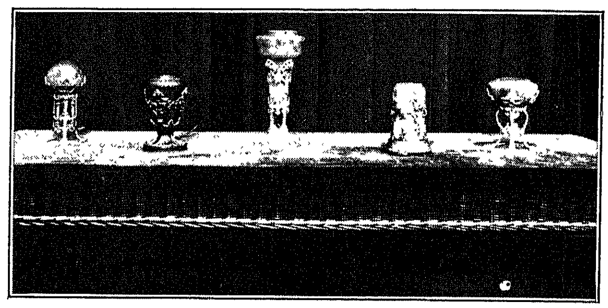

Fig. 4—Lighted Ornaments for Household Decoration

Residence Wiring. The increasing cost of residence wiring and the growing tendency toward unreasonable restrictions in the use of materials and methods are believed in certain quarters to be serious hindrances to the development of the residential use of electricity. As a result of this feeling study has been devoted during the last few years to the problem of surmounting these obstacles in the way of household electrical development.

It is believed that there are three important factors underlying the undesirable conditions mentioned. These factors are, first, lack of adequate skill in planning the average residence wiring system; second, lack of economical wiring materials; and third, the tendency to employ the electric wiring codes as obstructions to new development and progress.

The first condition is being corrected in many localities through the employment by the central station companies of home lighting experts and by the propagation of the so-called "Red Seal" plan. Looking forward to the amelioration of the other two unfavorable influences there is considerable agitation for the development of lighter and less expensive wiring materials, and for the modification of the electrical codes if necessary to permit the use of such materials.

Theatrical Lighting

The growing importance of stage lighting in dramatic production has led to the institution of a course in stage lighting in the Department of Drama at Yale University. This is perhaps the first serious attempt to teach lighting as a part of dramatic production. The course, which is open to students of some experience, involves a comprehensive study of the science of lighting particularly from the standpoint of history, physics, psychology, electricity, illumination, instruments, and control. This is followed by the study of

the use of light on the stage and by practise on regular productions.

Motion Picture Lighting. The almost universal use of panchromatic film and the closer attention to operating efficiencies and economies are two principal factors which have brought about in some studios the substitution of incandescent lamps for other illuminants. It has been found that the spectral quality of the light from incandescent lamps is well suited to panchromatic film and by their use better color rendition is obtained than with other illuminants. It is stated that by the use of incandescent lighting the labor and power costs for lighting are considerably reduced and, further, that it is found to be more flexible, more easily controlled, and more pleasing to those working under it than are other systems. Producers of the so-called talking pictures have found incandescent lighting desirable in order that the noises of arc lamps may not be recorded.

The usual lighting requirements for motion picture production call for a general illumination of from 200 to 500 foot-candles over the entire area to be photographed and, in addition, concentrated beams of from two to five times these values for modeling the principal actors or for bringing out certain parts in contrast with the rest of the set. The larger sizes of incandescent lamps up to those of 10-kw. rating are used.

One of the recent developments in equipment for amateur motion photography is a portable reflector containing a standard 500-watt, T20 bulb, 100-volt projection lamp to be operated on the usual 115-volt house lighting circuit. This over-voltage operation, while reducing the average life of the lamp from the normal figure of 50 hr. to about 5 hr., greatly increases the amount of light produced as well as its actinic value and renders possible the use indoors of amateur motion picture cameras which have heretofore been dependent upon outdoor illumination.

During 1927 there has been developed and placed on the market a new type of motion picture projector which utilizes a 60-ampere high intensity arc with an ellipsoidal reflector as optical condenser equipment. With this new type of projector it has been possible to obtain screen brilliancies equivalent to those previously obtained with a 120-ampere high intensity arc and the usual condenser lens system.

Exterior Illumination

Street Lighting

A tendency which has recently become evident in street lighting practise is the supply of 20-ampere series lamps from 20-ampere series circuits instead of through the medium of individual transformers from circuits carrying small currents. Besides the elimination of the individual transformers, this practise results also in the loading of the series conductor more nearly to its capacity and in the reduction of the voltage for which it must be insulated.

A method of remote control for street lighting circuits employing high frequency carrier-current impulses transmitted along the same conductors as the power current has been developed. The principal advantage of this method of remote control is that the power conductors are utilized for the transmission of control impulses without interference with their own function and without need for additional control conductors. It possesses a high degree of flexibility and is not subject to limitation of distance between transmitter and receiver to the same extent as is a pilot-wire control system. The first practical installation of the carrier-current control system was made in Schenectady, N. Y. Later installations have been made in Bayonne, N. J., Rochester, N. Y., San Francisco, Calif., and Boston, Mass.

Relation Between Street Lighting and Motor Vehicle Headlighting

Obviously there is a close relation between street lighting and motor vehicle headlighting. The practise in either field affects that in the other field.

If adequate street and highway lighting were everywhere available, there would be no necessity for powerful headlight beams. Since it is not likely to be economically practicable to illuminate all roads over which motor vehicles travel, there is no likelihood at present of eliminating such equipment.

On the other hand, as adequate lighting of streets and highways becomes more extensive, the practicability and desirability of driving for a considerable part of the time with dimmed or deflected headlighting is becoming more and more possible of realization.

Powerful headlights, such as are necessary to illuminate a highway, are subject to serious limitations. The known methods of eliminating glare from the eyes of other users of the highways are only partially effective and are not universally applied. Such glare is a source of discomfort and hazard. On densely traveled highways, the continual subjection of a driver's eyes to one headlight after another becomes quite serious.

Engineers who have given the most thorough study to the problem have reached the conclusion that its solution lies in the fixed lighting of highways carrying heavy traffic, and assert that suitable lighting is available and economically practicable in many such situations.

While the glare from automobile headlights is less serious in well lighted streets and highways, it is still objectionable, and since the use of powerful beams is unnecessary under these conditions, it is desirable to encourage the practise of avoiding their use.

The Committee on Street Lighting of the Illuminating Engineering Society has sought the cooperation of the Committee on Motor Vehicle Lighting of the same society in the consideration of this question. As a result of the joint deliberations, the following resolution

has been accepted as representing the views of both committees:

"JOINT RESOLUTION ADOPTED MARCH 7, 1928, BY ILLUMINATING ENGINEERING SOCIETY COMMITTEES ON STREET LIGHTING AND MOTOR VEHICLE LIGHTING

"RESOLVED, that in the opinion of the Illuminating Engineering Society Committee on Street Lighting and of the Illuminating Engineering Society Committee on Motor Vehicle Lighting, powerful headlights on automobiles as used in open road driving are unnecessary and undesirable upon adequately lighted streets. Upon such adequately lighted streets the practise of dimming or depressing headlight beams is desirable and should be encouraged.

"It is further the opinion of these committees that it is practicable at this time to provide such adequate street light for traffic thoroughfares of American cities. In general, street lighting on such thoroughfares is believed to be adequate for this purpose when the street area between curb lines is illuminated to an average horizontal intensity of one-quarter foot-candle or more. This illumination can be obtained even under unfavorable conditions by an expenditure of about 100 lumens per linear foot of street. Where light is applied most effectively, and other conditions are favorable, a materially smaller value of generated lumens will produce adequate illumination and will suffice for driving with dimmed or depressed headlight beams."

AUTOMOBILE HEADLIGHTING

The developments in automobile headlighting during the past year were characterized by structural improvements in headlamps and accessories and in the more extended use of the depressible beam system with two-filament lamps.

Among the difficulties encountered in attempting good headlighting has been the fact that headlamp construction often has been so poor that permanency of adjustment could not be expected. Also, headlamp mountings have been, in many cases, so badly designed and made that close adjustments have been difficult to obtain and when once obtained have been insecure. With respect to these matters there has been a material betterment. Furthermore, the incandescent lamps used are being made to closer factory standards, particularly with respect to positioning of the filament, (axial alinement and light center length), so that the day seems to be approaching when focusing adjustments on headlamps can safely be abolished. This will bring a great relief to the motorist and better average headlighting conditions on the road.

The belief has taken strong hold that headlight beams with a wide lateral spread below the horizontal are advantageous in night driving and the tendency is to use front glasses on headlamps which will give these wide spreads. This has brought up the difficulty that if the total available flux of light from a 21 cp. incandescent lamp is spread over as great an area as it seems to be desirable to illuminate, the beam intensities fall below a desirable limit, so that seeing is impaired. The use of the 21 cp. lamp is very extensive. In many states the use of higher candlepowers is prohibited. From a technical standpoint, however, it appears that proper illumination over the wide area which should be illuminated involves the use of higher candlepower lamps. Both the Lighting Division of the Society of Automotive Engineers Standards Committee and the Motor Vehicle Lighting Committee of the Illuminating Engineering Society, the former in connection with the preparation of the specifications for dual-beam equipment mentioned below and the latter in its last report have recognized this condition and have pointed out that the logical solution of future design involves a raising of the limit to 32 cp., a change which does not involve overloading the electrical equipment of the car.

The same committee of the I. E. S. during the past year has produced a draft of specifications for laboratory tests of optical characteristics of electrical headlamps intended to cover the so-called dual beam equipment for motor vehicles, and eventually to supersede the former headlight test specifications of the I. E. S. for the test of the single beam equipment. The Society of Automotive Engineers has cooperated in this matter and has adopted these specifications as part of its code of recommended practise. It is hoped that after a suitable trial period these specifications, with or without slight modifications, will be suitable for proposal to a sectional committee organized under the American Engineering Standards Committee procedure for adoption as an American standard.

The dual beam headlighting system discussed at some length in last year's report has been approved by all states as legal and has met with wide popularity. A large proportion of the new cars is now being provided with this equipment. By its use two things are accomplished: first, a great amelioration of the glare difficulty is obtained by the use of the depressed beam, and second, since the driving beam can be removed from the eyes of passing drivers, the adjustment of the headlamps may be such that the top of the beam is of higher candlepower than with the fixed beam equipment, thus providing a better driving light where the absence of oncoming cars renders it practicable to keep the beam in its normal position.

A promising research project directed toward the determination of the most satisfactory methods of automobile headlighting is being carried out at the Bureau of Standards under the technical direction of the Research Committee of the Society of Automotive Engineers with funds provided by the National Automobile Chamber of Commerce. The object of this investigation is to carry further by means of road tests, supplemented by laboratory work, experiments to ascertain the headlighting requirements of the

driver under various conditions and how best to fulfil these requirements under definite conditions. The first part of this research, designed to show the effect on visibility distance of various road conditions and lighting distributions, has been completed. Progress is being made on the second part in which the effect of approaching lights will be considered as an additional factor.

Signal Lighting for Traffic Control

On November 15, 1927, under American Engineering Standards Committee procedure there was approved as an American Standard a Code of Colors and Forms for Traffic Signals for Highways and Vehicles. This code includes lights used upon vehicles and also luminous signals used for traffic control, but it does not include non-luminous signs. The code establishes the use of green for GO, red for STOP, and yellow for CAUTION, and gives a scientific specification for these three colors. The code includes the type of signal to be used at railroad grade crossings to indicate the approach of a train.

The subject of non-luminous traffic signs is to be covered in a report of a committee of the American Engineering Council on Street Signs, Signals, and Pavement Markings. This A. E. C. Committee has been at work for more than a year and has nearly completed its report, which includes the choice of colors, forms, wordings, mounting positions, mounting heights, and various other details of street traffic signs as well as recommended practises for pavement markings. It is attempting to standardize the control of right and left turning movements where luminous signals are used in the hope of achieving some uniformity in the use of such signals. It favors the use of red and green only rather than red, yellow, and green; but where yellow is to be used it is hoped that it may be used in a uniform manner in all communities. Its report is now in the hands of a sectional committee of the A. E. S. C.

The A. E. S. C. code already approved provides that automobile headlights shall be white, yellow, or some intermediate hue. Tail lights are to be red and rear signaling devices are to be yellow. Other red and green lights are not to be displayed on either the front or the rear of vehicles. Conformance to this code will require the abandonment of red and green lights for route markers and for rear signaling devices.

In line with the standardization of the use of colored lights, the American Engineering Standards Committee has already approved of green as the standard color for exit lights from theaters and similar buildings.

Sign Lighting

The National Electric Light Association, in the spring of 1928, sponsored two schools of electrical advertising which were held at the respective lighting institutes of the Edison and National Lamp Works of the General Electric Company. In addition to the technical aspects of electrical advertising, the schools stressed the necessity for cooperation between the various branches of the industry for the purpose of improving the value of this advertising medium.

The projection of advertisements upon low clouds in the sky has been made possible by the development of a huge lantern slide projector illustrated in Fig. 5. The application of this method has not as yet proved generally practicable, being decidedly limited by meteorological conditions.

The animated bulletin board type of sign consisting of figures painted with saturated colors and illuminated alternately by light of different hues continues to grow in popularity in spite of its limited color range.

Porcelain enameled steel letters are being used more extensively than in former years, particularly in connection with large roof signs. Their ability to withstand exposure to the weather and the ease with which they may be cleaned are important advantages over painted letters. The recent use of chromium-plated

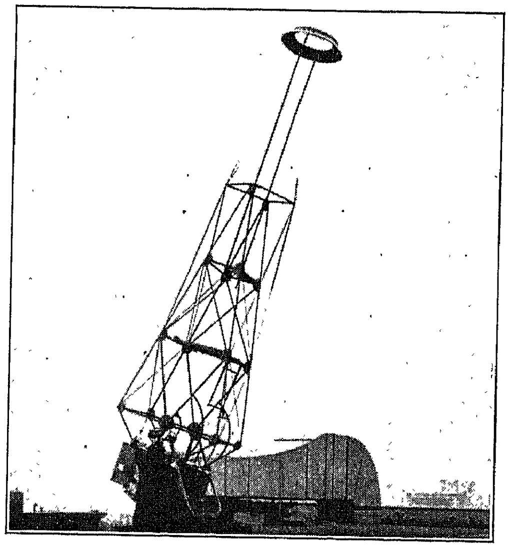

Fig. 5—Sky Projector

channel letters and borders in electric signs is one of the latest recorded developments in the sign art. The effect is apparently to multiply the number of lamps in the sign in consequence of the specular reflections from the polished surfaces. The non-corrodible quality of chromium plate renders it especially suitable for this service.

The increasing popularity of the neon tube is one of the notable developments in this art. It has been stated to the committee by one of the leading manufacturers that during the last four years about 700 neon electric signs have been installed in the New York metropolitan area and that more than 4500 such signs have been installed throughout the United States.

Lighting of Building Exteriors

The floodlighting of office and public buildings has advanced rapidly during the last few years. Architects have manifested greater interest in lighting as a

means of bringing out pleasing features of design and in consequence many buildings at present under construction are provided with ample wiring at the proper places for floodlighting. In the case of tall buildings the trend of practise is to light the upper stories which are visible from the greater distances and for the lighting of which facilities are afforded by the modern setback style of construction. During the past year there has been a distinct tendency toward the employment of color in floodlighting. The instances of the use of color range from small installations with touches of color here and

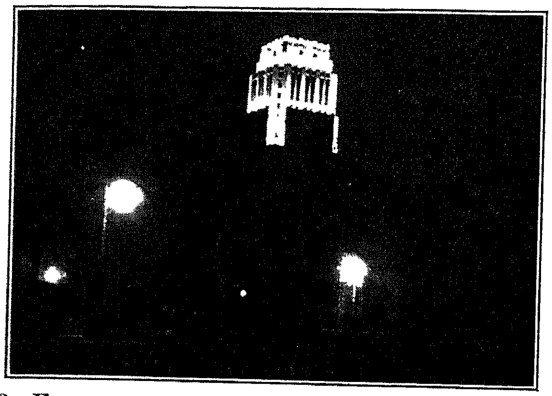

Fig. 6—Floodlighting of Edison Building, Philadelphia, Pa.

there to large buildings whose entire facades are bathed in light of one or more colors. Perhaps the most notable recent example of colored floodlighting is the new 23-story building of the Philadelphia Electric Company which is lighted above the fifteenth story with continuously changing tints of four colors. This installation (illustrated in Fig. 6) comprises a total of

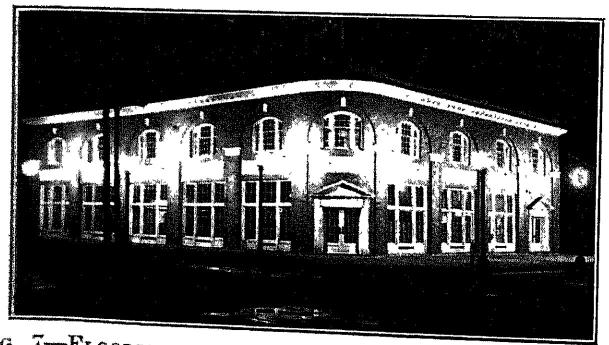

Fig. 7—Floodlighting from Ornamental Street Lighting Posts

467 projectors consuming 262 kw., which is equivalent to about 9 watts per sq. ft. of lighted area. The colored lamps, which are connected directly across the line, are supplemented by clear white lamps connected in series with motor-driven dimmers. By this means the colors are diluted with white light in continuously changing proportions. The colored lamps comprise about two-thirds of the total wattage and the clear lamps one-third.

The supply of floodlighting projectors from series street lighting circuits is an interesting development of the recent past. In this class of installation the floodlights burn on the same schedule as the street lamps, and are owned, installed, and maintained by the electric service company.

Another interesting method (illustrated in Fig. 7) of floodlighting buildings not exceeding 100 ft. in height, is the installation of projectors in the ornamental tops of street lighting posts located along the curb. In addition to the projection lamp in this type of installation an auxiliary lamp of about 200-watts rating is required in each post top in order to raise its brightness to a point where its appearance bears out its function as a light source. This type of installation has the merit of a pleasing appearance in the daytime as well as at night and is particularly well adapted to those cases where no out-of-sight location can be found for the projectors.

Lighting of Railroad Yards

Floodlighting is becoming recognized as the standard method for the artificial illumination of railroad yards and its application is, therefore, rapidly extending. The need for more exact engineering data and method in designing floodlighting installations and selecting lighting units has been recognized. The Committee on Illumination of the Association of Railway Electrical Engineers has continued its active study of this subject, and, with the assistance of a subcommittee comprising specialists in photometric and illuminating engineering work, has prepared a "General Procedure for Photometry of Incandescent Floodlights" which it has recommended for adoption as standard practise for testing and rating floodlighting projectors.

Railroad Signaling

During 1927 automatic signals were installed upon 5127 mi. of railroad. This record has not been equaled in any previous year. The preference for light signals is indicated by the fact that of the total number of signals installed during 1927, 74 per cent were light signals and 26 per cent were semaphore. The proportion of light signals tends to increase from year to year. Of the light signals installed during 1927, 82 per cent were colored lights, 16.8 per cent were position lights, and 1.2 per cent were color position lights. One of the outstanding developments of 1927 was the placing in service of a centralized dispatching system on the Ohio division of the New York Central Railroad. This installation represents the accomplishment of the idea of operating trains by signal indication without written train orders or operators at intermediate stations. All signals and passing side switches are power-operated and under the control of the dispatcher at a central point.

Lighthouses

Since the first practical application of the incandescent electric lamp to large lighthouses at Cape Henry

Light in 1922, practically all of the coastal lighthouses of large size in this country have been so equipped wherever central station service is available or where a local generating plant can be maintained. During the past year ten light stations and three lightships were equipped with electricity. Small electric lights, the current for which is supplied by a battery of primary cells, are to some extent being substituted for oil burning post lights on inland rivers and similar locations. These outfits have been designed to operate without attendance for several months.

A relatively recent development in the application of electricity to the lighthouse service is the automatic lamp changing device, actuated by a no-voltage relay, which swings into focus and lights a spare lamp in the event that the first lamp burns out in operation. Though commercial types of incandescent electric lamps have been found satisfactory in lighthouse lenses of the smaller sizes, and though they produce adequate beam intensity in lenses of any size, they are not well adapted for use in large lenses designed for other illuminants because the filament is not large enough to provide sufficient vertical divergence of the beam in fixed lenses, and in revolving lenses the length of flash provided is of too short duration. Considerable experimentation along the lines of variations of filament shape and frosting of bulbs has resulted in the development of several lamps for this service which represent a great improvement over the general service types.

Lighting for Aviation

During 1927 much work has been done in the lighting of airways in order to promote the safety of night flying. At the present time 5800 mi. of air route are provided with flying facilities which include beacon lights 10 mi. apart, or closer where required, lighted intermediate landing fields 30 mi. apart, radio communication service for weather information and forecast, reports of arrivals and departures, and direction and control of aircraft in flight.

The beacon lights are erected on 50- or 75-ft. steel towers at the bases of which are chrome yellow arrows 56-ft. long to indicate the line of flight. The number of the beacon is painted in black on the arrow for daytime identification. The beacon light consists of three units, a revolving searchlight synchronized with two flashing red course lights. The revolving beacon has a 24-in. parabolic mirror and a 1000-watt, 110-volt T20 incandescent lamp designed to yield an average life of 500 hr. The beacon develops a beam intensity of between two and three million cp. Its axis is elevated two deg. above the horizontal and it is rotated about a vertical shaft by a motor and worm gearing at a rate of six rev. per min. Auxiliary contactors on the vertical shaft interrupt the current to the course lights according to a code by which the pilot identifies the beacon.

Each course light consists of a 500-watt, G40 incandescent lamp in a 14-in. parabolic reflector with a red or amber 30-deg. spreadlight cover glass. The electric circuits are controlled by astronomical clocks which turn the lights on at sunset and off at sunrise. Where commercial electric service is not available two-kw. full automatic gasoline engine generators are installed in duplicate. In the event of engine failure a relay places the stand-by generating unit in operation.

Intermediate landing fields are marked with a revolving beacon, a boundary lighting system, obstruction lights, and an internally lighted wind cone. The fields usually have two landing strips at right angles to each other, each about 500 ft. wide and 2000 ft. long. The boundaries of the landing strips are marked by 15-watt or larger multiple lamps in clear white refractor globes spaced about 300 ft. apart or by series lamps of equivalent candlepower. Green range lights mark the favorable approaches and 25-watt or larger multiple lamps in red globes are mounted on all neighboring obstructions.

To meet the requirements for terminal fields 425 airports have been established or are under construction by municipalities in the United States. The Department of Commerce has established an airport section to cooperate with city officials for proper selection and development of airports. Extensive tests were made during the past year in the landing of aircraft at night under varying conditions and floodlighting systems.

The outstanding developments in airport lighting during the year were a new system of grouping of incandescent floodlight units on one or more sides of the landing field, an intermediate size dioptric floodlight unit using the 5-kw. incandescent lamp, illuminated field markers and wind-direction gages and a 55-ampere high intensity arc floodlight unit with 2 deg. vertical and various degrees of horizontal spread of beam. Neon tube beacons and boundary lights have been advanced in development during the year and it is understood that in Great Britain and Germany they are employed very generally in lighting for aviation. A practical method has been demonstrated for automatically controlling landing field floodlights through switches actuated by the noise of the airplane or by a whistle of distinctive tone mounted on the plane.

Lighting for Night Recreation

Artificial lighting is being used more and more to extend the uses of recreational areas into the dark hours. Lighting installations for night tennis, football, races, bowling on the green, hockey, horseshoe pitching (quoits), and indoor baseball are numerous and assure the practicability of night sports. Fig. 8 shows a court illuminated for playing quoits after dark. Extensive investigations at Lynn, Mass., indicate that in no very distant future the great national game of baseball may be played at night under artificial illumination.

During the past year special progress has been made in the application of artificial light to swimming pools.

In addition to levels of illumination of the order of 5 to 10 foot-candles over the entire pool area to insure safety and comfort it has been found desirable and feasible to provide, in the deeper parts, under-water illumination from units below the surface. Equipment which can be installed quite economically has recently been made available for this service.

Christmas Lighting. More attention has been paid to decorative Christmas lighting this year than ever before. Over fifty communities conducted contests during the holiday season in the decorative lighting of residences, all of which were successful in greater or lesser degree. Greatest interest, as manifested by the largest number of entries, has come where the contest has been divided into several classes or districts so that moderate homes were not expected to compete on an equal basis with wealthy homes. In Fig. 9 is illustrated an example of the result achieved by effort applied in this direction.

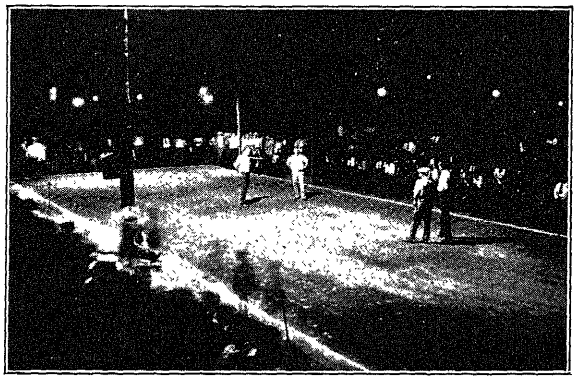

FIG. 8—ILLUMINATED COURT FOR QUOIT MATCHES

UNDERWATER LIGHTING AND DIVING LAMPS

The standard diving lamp adopted by the U. S. Navy and approved by marine salvage companies now consists of a 1000-watt G40 extra heavy glass bulb lamp, 115-volt range, with concentrated filament construction. These lamp bulbs are tested to withstand a pressure of 150 lb. per sq. in., which suffices for submersion to a depth of 300 ft. The bulb is mounted in a housing some 18 in. long with a non-tarnishing metal reflector 11 in. in diameter. In operation the lamp bulb is in direct contact with the water, being protected only by a heavy wire screen across the mouth of the reflector. The problem of overcoming water leakage has been solved by the use of a special insulating sleeve surrounding the base of these lamp bulbs. To prevent the crushing of the lamp base and the seal, which are the weakest points of the structure, special reinforcement has been introduced. These lamps have proved very useful in recent salvage operations on the submarine S-4. Although the water near the bottom was very muddy, the divers there engaged reported good visibility at distances from 3 to 6 ft. Experiments have been conducted to ascertain whether colored light would be more effective than white light in promoting visibility under water, but the results have been chiefly of a negative character.

During the past summer underwater lamps were used in a study of tropical marine life off the coast of Haiti. Both clear and colored lamps were used and the attracting power of light for certain fish seemed well demonstrated. It is reported that electric incandescent lamps are in use as bait by Japanese fishermen.

LIGHTING FOR AGRICULTURE

Recent investigations into the relation of light to plant growth and maturity have followed three paths, first, the relative effects of radiations of different wavelengths, second and third, the effects of variations in the relative and absolute lengths of the alternate periods of light and darkness. Different varieties of plants do not seem to react in the same way to the same conditions of irradiation. It has been reported that the growth of some plants has been stimulated and the content of certain valuable ingredients increased by exposure to the ultraviolet end of the spectrum of sunlight. Other investigators have concluded that, in general, the ultraviolet portion of the spectrum of sunlight has no great effect on plant growth, time and amount of flowering, or the weight of tissue produced. It has been observed that certain pigments, as the red in mignonette lettuce and the purple in purple cabbage, are intensified by violet and ultraviolet radiation. It has been shown by several experimenters in this field that ultraviolet radiation of wave lengths shorter than 248 millimicrons is very injurious to growing plants.

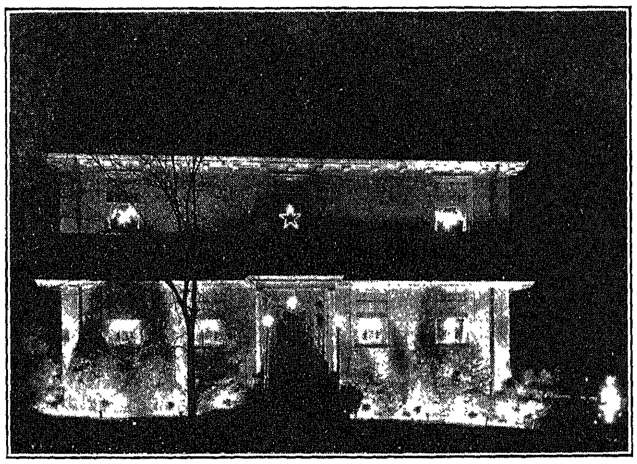

FIG. 9—DECORATIVE LIGHTING OF HOUSE FOR HOLIDAYS

Previous investigations have shown that long periods of illumination produce in some plants increased vegetative growth while in other plants they bring about early maturity. Recent experiments with the variation of the absolute lengths of the alternate periods of light and darkness (their relative lengths remaining constant) have led to the conclusion that with plants in which flowering is favored by short days, as well as with those in which the opposite is true, the general effect of relatively short alternations of light

and darkness on reproductive activities is much the same as that produced by long days or continuous illumination. However, it was also observed that the short light-darkness alternations may bring about more or less serious nutritional disturbances. As the periods are shortened the plant seems to be weakened until a point is reached at which the growth begins again to improve. This point in one case was equal periods of 15 sec. of light and darkness. In another case it was found that periods of 0.004 sec. duration produced the same rate of assimilation in the plant as did continuous illumination.

The attraction of light for insects has been used for many years in luring them to their destruction. A recent application of this principle was made in Alabama where fruit worms had caused severe losses in the tomato crop. With 100- and 200-watt lamps and flat reflectors suspended 5 ft. from the ground and over pans of water covered with kerosene, the protection was reported to be so complete that only 35 worm-infested tomatoes were found in two acres, whereas neighboring unprotected fields suffered losses from 30 to 50 per cent.

That color is a factor in the attraction has been shown in some results obtained at the State Experiment Station at Geneva, N. Y. It was found that "tent caterpillars," a most ravenous insect pest, would leave young apple twigs and gather in places where there was plenty of light though little fodder. With differently colored lights, the apparently hungry caterpillars usually went directly to those of a pale yellow. Some preferred a deeper yellow, but red light appealed to only a few.

From other quarters information has been received that while many experiments, some of them very careful tests, have been made with lights in the control of different insect pests such as the cotton worm, cotton boll weevil, codling moth, Japanese beetle, etc., the results have not been sufficiently favorable to indicate that any material help may be expected from the use of light traps under the conditions of experimentation. It is believed that there is room for considerable further experimentation in this field, as with lights of different colors and different intensities.

The use of artificial light in poultry houses during the winter months has become a common practise on many poultry farms. The usual method is to turn on the lights for a short period morning and night in order to extend the period of daylight, thus stimulating the activity of the hens and increasing their food consumption and egg production. In addition to the use of artificial light in this connection, electricity is being used in experimental work to furnish ultraviolet rays to young chicks and also to laying hens which are kept confined where they do not get direct sunlight, the effect of the ultraviolet radiation being to promote bone formation and to prevent the occurrence of leg weakness, a condition resembling the disease in human beings known as rickets. The more common practise, however, is to accomplish this result by administering with the chickens' feed a ration of cod liver oil which has the same specific effect as ultraviolet radiation.

Other Topics

Sources and Applications of Ultraviolet Radiation

The general interest in the health promoting use of ultraviolet radiation has stressed the need, on the one hand, for windows transmitting all of the sun's short wave radiation, and on the other hand, for artificial sources emitting little or no radiation of higher frequency than that present in direct sunlight. The former need has been met by a variety of more or less satisfactory materials for use in place of ordinary window glass. Of these materials the degree of transparency to ultraviolet radiation varies greatly. Moreover, the transparency of certain materials tends to deteriorate with exposure.

The latter need arises from the hazard incidental to the use by laymen of the high intensity, high frequency ultraviolet sources formerly used only by the medical profession, and also from a recent tendency to attribute the maximum therapeutic value to those wave lengths in the immediate neighborhood of 300 millimicrons. This need has been met by the use of the new window glasses as filters in connection with arc lamps which have long been used as artificial sources of ultraviolet radiation. However, much attention has been given to the problem of developing a new source characterized by a maximum possible emission in the region from 280 to 320 millimicrons, with no emission of shorter wavelength and a minimum of radiation of longer wave length. It is expected that such a source of ultraviolet radiation will appear on the market within the next year.

The types of artificial sources at present available are being widely sold for use not only by physicians but for home use under medical supervision. Artificial "solariums" are being generally established in connection with athletic clubs, Y. M. C. A.'s, Y. W. C. A.'s, and sanitariums throughout the country. Baby clinics primarily for ultraviolet treatment and prevention of rickets are in operation in many large cities.

Two new industrial applications have been well established during the past year. The application of ultraviolet radiation from artificial sources to the hardening of the varnished surface of patent leather has been successful in effecting a higher quality of product with a much shorter treatment than was possible by the former method of exposure to sunlight. The exposure of dried milk powder to ultraviolet radiation has resulted in the production of an infant food having marked antirachitic properties. A similar use of ultraviolet radiation in connection with the preparation of other food materials is under investigation.

Photometry

Recent progress in photometry has taken the form of refinement of existing methods and instruments and of increased knowledge of the characteristics of the photoelectric cell. The advent of the four element vacuum tube has made it possible greatly to improve the sensitivity, speed, and precision of photoelectric spectrophotometry. The photoelectric cell containing a monomolecular layer of caesium which has recently become available, represents a distinct advance over the earlier types in stability of color sensitivity and in approach to eye sensitivity.

A recent development in the photometry of floodlights and other projectors has been the use of a concave spherical mirror in place of a diffusing hemisphere for integrating the light flux over a unit of solid angle.

The standard method for photometry of floodlighting projectors, mentioned elsewhere in this report, which has been formulated by the Committee on Illumination of the Association of Railway Electrical Engineers, is intended to render possible the comparison of results of photometric tests made on projectors by different laboratories. This is achieved by standardization of testing conditions and methods of computation of results from test data. Briefly, the method provides that the light flux within a solid angle of one square degree be measured in an integrating device at a distance of not less than 100 ft. Observations are taken at approximately 100 stations uniformly spaced throughout the beam, and in addition, at a series of stations on eight equally spaced lines radiating from the axis of the beam and extending to the limits of the lighted area. This method of integrating the light output over a solid angle of one square degree minimizes erratic results due to traces of filament image in the beam. Since the beam limits are defined in terms of the maximum candlepower value, individual test results of single projectors show some variation in beam efficiency. Further refinement of the method is under consideration with a view to reduction of these variations.

The great differences in the intensities and the spectral characteristics of the ultraviolet radiations from the various sources make it desirable to be able conveniently to compare the radiations from several sources in terms preferably of some standard unit of intensity. Unfortunately no convenient method of accomplishing this has been standardized, though it has been suggested that the intensity of the ultraviolet component of sunlight at least may be inferred from photometric measurements, the factor of proportionality having been determined for the given locality by radiometric measurements in the laboratory.

Miscellaneous Applications of Light

An interesting and novel application of light is in a device recently developed for measuring the change in length of a small specimen of magnetic material upon magnetization. This change of length is of the order of a billionth of an inch. In this apparatus the image of an illuminated portion of a ruled grating is reflected back upon another portion of the grating by a pivoted concave mirror which is arranged to tilt slightly when the length of the specimen changes. Behind the second portion of the grating is a photoelectric cell. As the mirror tilts the image moves across the grating, causing a variation in the amount of light transmitted to the photoelectric cell. The response of the cell, as indicated by a sensitive galvanometer, is a measure of the tilt of the mirror and of the change of length of the specimen.

A recent application of ultraviolet radiation and the photoelectric cell is in a device for the automatic concentration of ores. The crushed raw ore on a belt passes under a source of ultraviolet radiation which causes the pieces of valuable material to fluoresce strongly, while the pieces of worthless rock remain unaffected. A photoelectric cell screened from the ultraviolet radiation picks up the visible light of the fluorescent material and actuates a device which separates this material from the rock.

International Consideration of Illumination Topics

The occasion of a plenary meeting of the International Commission on Illumination in America will be marked by an International Illumination Congress during the week of September 24, 1928. In addition to reports of technical committees of the I. C. I., there will be papers and discussions on a variety of lighting topics. This meeting is expected to bring together leading lighting experts from the several countries and bids fair to advance understanding through the exchange of technical information with results beneficial to all participating countries.

Preston S. Millar, *Chairman.*

CONTRIBUTORS OTHER THAN MEMBERS OF COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT

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W. B. Powell, Chairman, Sectional Committee on Street Signs, Signals, and Markings of American Engineering Standards Committee.

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C. B. Veal, Research Manager, Society of Automotive Engineers, Inc.

Electrochemistry and Electrometallurgy

ANNUAL REPORT OF COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY*

To the Board of Directors:

The Committee on Electrochemistry and Electrometallurgy makes its annual report as follows:

The revision of the Institute's standards for storage batteries which was proposed by this committee several years ago has been completed by Working Committee No. 37. The revised standards were adopted by the Board of Directors February 16, 1928 and have been published.

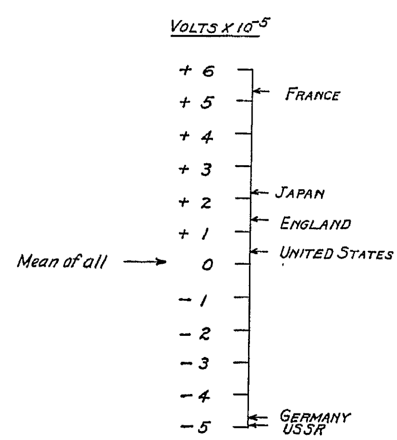
Standards for the international electrical units continue to receive attention at the National Standardizing Laboratories. These standards are the basis for electrical measurements of both the engineer and the physicist. The standards for the international system of units are essentially electrochemical and it is appropriate, therefore, to review briefly the present situation in regard to them. Since 1911 fundamental measurements of current have been based upon wire resistances and the value determined for the Weston normal cell by an international technical committee which did its experimental work in Washington during the year 1910. At that time values to be assigned to the wire resistance coils were agreed upon. No detailed specifications for either the standard cells or the silver voltameter which serves as the international standard for the measurement of current were agreed upon, but the work of preparing such specifications was continued by several of the national laboratories until interrupted by the War and a high degree of uniformity was attained in the voltameter measurements.

The interlaboratory comparisons of standard cells were also interrupted by the War and it is only within recent months that we have obtained comparisons of the value of the volt in the principal countries. Direct exchange of standard cells has been made between the Bureau of Standards and several foreign laboratories. Several groups of cells have been taken also to the various national laboratories by representatives of the Central Chamber of Weights and Measures at Leningrad. A report by M. Malikoff and M. Kolossof has recently communicated the results of their comparisons. On the basis of their report as well as the direct exchange of cells, the accompanying figure has been prepared to show the relation of the volt in six countries at the present time.

The maximum differences are rather larger than was to be expected. This should not be interpreted as meaning that the saturated cell is not reliable or reproducible since the value for the cell is a derived value and may therefore include uncertainties in the value of the ohm or errors in the use of the voltameter, or whatever other means may have been employed for determining the cell values from time to time.

The procedure for maintaining the volt by means of the Weston normal cell at the various laboratories differs very greatly. A redetermination of the international ampere by means of the silver voltameter has been undertaken by the Bureau of Standards. Work of this character has not been done previously for 15 years.

Whatever the outcome of the present discussions as to the advisability of continuing the international system of electrical units or changing to the absolute,



RELATIVE VALUE OF THE VOLT IN SIX COUNTRIES AT THE PRESENT TIME

c. g. s. system may be, the maintenance of the reference standards, particularly the standard cell and the wire standards for resistance will be none the less important. If the absolute units are eventually adopted in place of the present international system, the silver voltameter and the mercury ohm will be discarded.

The fifty-third meeting of the American Electrochemical Society included a symposium on the chemical production of electricity. Eighteen papers were presented on primary cells, storage batteries, rectifiers, and electrolytic condensers. The feasibility of making dry cells without the use of manganese ore was described in several papers. Graphitic oxides have become a commercial possibility as a substitute for manganese dioxide, but no immediate change in the construction of dry cells is likely. The graphitic oxides, however, should find other applications where a convenient source of loosely held oxygen is needed. The absorptive

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Lawrence Addicks, A. N. Anderson, T. C. Atchison, Farley G. Clark, Safford K. Colby, E. B. Dawson, F. A. J. Fitzgerald, W. E. Holland, F. A. Lidbury, C. G. Schluederberg, J. A. Sede, Magnus Unger, John B. Whitehead, J. L. Woodbridge, J. L. Yardley.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

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properties of finely divided carbon have also made possible the construction of primary cells of large capacity, subject only to the renewal of the zinc and the electrolyte.

The development of satisfactory aluminum electrolytic condensers has been important in the telephone field. These condensers have a service life yet to be determined. Some have been in service more than five years and others, operating under test conditions in the laboratory, have passed eight years. The capacity depends somewhat on the formation and the conditions of service. Condensers for 24-volt circuits have a nominal capacity of 1000 μ f. and weigh about 40 lb.

An electrical distillation method described in a recent paper before the Electrochemical Society has been developed for the manufacture of chemically pure hydrochloric and nitric acid. By this means a continuous process has become possible, utilizing electrical energy in place of fuel, with added advantages of greatly reduced cost and an improved product.

Electric melting of steel and iron has maintained its already established position. Complete data are not available on furnace installations during the past year, but a considerable number of new installations include the 'Lectromelt furnaces. The United States is believed to lead the world in the production and utilization of the electric furnace. One noteworthy installation for which an order has been placed during the early part of 1928 is for a 60-ton steel-melting furnace to have an installed transformer capacity of 20,000 kv-a. The phrase "electric steel" has now become a trade mark of superior quality.

Increasing interest has been noted in the possibility of providing greater uniformity in composition and physical properties of cast iron and this affords a promising field for electric furnaces.

The induction type of furnace, sometimes referred to as the high-frequency furnace, has appeared in the ferrous field for the production of alloy steels. In the past, the opinion has been held that the induction furnace would not be useful in the iron and steel industry although it had found a place for itself in the nonferrous field. At the present time some are inclined to think that the widest application for the induction furnace will eventually be in the iron and steel industry. The design of a one-ton steel melting furnace of the induction type is now in the development stage. During the past year new installations have been devoted largely to the manufacture of high-grade special steels and alloys.

Another development in the electric furnace field has been the introduction from France into this country of the Miguet electric furnaces. Electric furnace engineers have recognized the desirability of using large electrodes in order to produce more efficient operation and better quality of production. The electrode in the Miguet furnace covers the entire molten charge, that is, the diameter of the electrode is equal to the diameter of the bowl.

Electric melting in the brass industry is a development of comparatively recent years but it has now become firmly established by affording a control of the product that was previously lacking and by improving working conditions. The smaller brass foundries have been somewhat slower in adopting electric heat for melting than the larger plants in the wrought brass industry, but relatively small furnaces of the single-phase type are now becoming more common.

Increased interest has been shown in the wide application of electric furnaces to various other industries and of particular note is the recent application of electric furnaces to glass melting. This has been a difficult problem to which extended research has been devoted and it is only recently that practical installations have been made. The glass charge is used as the resistor.

Industrial electric heating and annealing has continued to advance. Recent conferences on this subject have been held at Purdue and Yale Universities. A notable example of electric heating and annealing has recently been carried out at the Bureau of Standards in connection with the cooling of the largest disk of optical glass ever cast in America. Refractories for furnaces used in the glass industry have been improved during the year by the introduction of Corhart cast refractory blocks. These are made by fusing aluminous silicious material in an electric furnace and then casting the material in blocks at a temperature about 1900 deg. cent. This material on cooling has a dense interlocking crystalline structure which is nonporous. Tests which have been made in the glass industry show that it has much longer life than any other refractory previously used in that work.

Among the resistors for furnaces, there has been further development in what is known as the Globar elements. These elements are made of silicon carbide. The idea of using this material as an electrical resistor in high temperature work is not new, but it has not been used extensively until recently. Silicon carbide has a large negative temperature coefficient and when used as a resistor was not entirely stable. That is, its resistance tended to increase after a short period of use. During the past year a much more stable resistor of this type has been made and these are now obtainable in large sizes, some as large as 2½ in. in diameter and 5 ft. long with an electrical rating as high as 25 kw. per bar. Another difficulty with these resistors has been overcome by a method developed within the past year for improving the electrical contact at the terminals.

Chromium plating continues to be the center of interest in the electroplating field. Clearing of the patent situation will doubtless further stimulate the use of this metal in electrodeposition. One of the most interesting developments during the past year has been

in connection with chromium plated tools. The industry has reached a stage where the demand for chromium plated-ware is far in excess of the supply.

Cadmium plating is proving valuable as a preventative of rust and its use is growing on this account.

Many attempts have been made to develop satisfactory methods of electroplating aluminum and its alloys, but few of these hitherto described have been successful. Adherent smooth deposits of nickel and other metals on a roughened aluminum surface have now become possible by methods recently described to the Electrochemical Society. These methods vary in detail and are adapted to pure aluminum as well as to each of a number of its alloys. The plated aluminum has advantages by reason of its improved appearance as well as its resistance to abrasion.

The Copper and Brass Research Association has been instrumental in making the uses for copper and brass better known to the public. Evidence of this is found in the fact that the use of brass pipe has increased over 200 per cent in the last three years. The older copper refineries are said to be planning extensive modernization programs chiefly along the line of reducing the power cost.

The output of electrolytic zinc continues to grow as a result of available cheap zinc concentrates which can be handled by this method. This affords a valuable outlet for electrical energy which is likely to increase. The output of electrolytic zinc from aqueous sulphate solution is estimated at the present at 500 tons a day as compared with 100 tons at the close of the War. An increased capacity for the production of electrolytic zinc is forecast for the coming year as several large electrolytic plants have recently been built or projected and some chemical engineers say the time is not far distant when virtually all zinc will be electrolytically refined, as in the case of copper, because of the better quality of the product. The development of the de Laval electrothermic process in Sweden by American interests may, however, have an important result in this field.

In the lead field, additional Betts plant capacity is being built and it seems possible that the demand for lead which is very low in bismuth may become more general. At Kellogg, Idaho, and in Peru, the Tainton process of recovering lead electrolytically from leach liquors along lines analogous to the zinc work is in development.

In the field of aluminum and its alloys a new form of sheet material combining the strength of the alloy and the resistance to corrosion of pure aluminum has recently appeared under the name, Alclad. This consists of a heat treated aluminum alloy base with a smooth nonporous surface of pure aluminum alloyed to the core. This material is expected to overcome serious difficulties which have been experienced with aluminum alloys in the past. Magnesium is finding increasing use in the aluminum alloys of high strength. Uses for the very pure aluminum prepared by the Hoopes process are increasing.

The chief interest in the production of metals from fused electrolytes has recently centered around the large aluminum plant now being constructed at Arvida, Canada. The capacity of this plant is planned to equal the present world production of aluminum. Two sections of the plant have been put in operation. The construction of all-metal airplanes is expected to be an important factor in providing an outlet for the greatly increased production of the light metals.

Beryllium has risen to a position of importance among the metals produced from fused electrolytes. Three per cent of Beryllium added to iron produces a steel and an equal quantity added to copper makes a valuable bronze. Rare metals are being produced on a limited scale by the electrolysis of fused salts and of these the most notable is probably Zirconium.

The use of electrolytic hydrogen in the production of synthetic ammonia has been increasing. Several large installations are planned for this year in Japan and Norway. One of the objections in the past to the electrolytic manufacturing of oxygen has been the lack of a market for the byproduct, hydrogen. The use of atomic hydrogen in welding operations promises a possible balance to make possible the economic production of electrolytic oxygen and hydrogen in place of liquification equipment now used for making oxygen alone.

A new type of oxy-hydrogen cell has recently been designed to operate at high temperatures without undue deterioration. The larger cells are rated for 2.3 volts at a maximum current of 15,000 amperes. These cells are said to be able to follow the normal load in somewhat the same way as the storage battery when charging at a variable rate and to do this without any great change in efficiency. Off-peak energy converted to direct current can be absorbed with a consequent improvement in load factor and it is claimed that the cells may be operated on 3300-volt circuits. It is suggested that under some conditions the large scale production of these gases at a low cost might reach a point where they could be used in the production of gas for heating purposes.

The materials for nitrogen fixation are so universally available that the problem of nitrogen fixation and the use of the products for fertilizer, munitions, or otherwise is largely a problem of national requirements, as to which each nation can reasonably hope to be independent. The development of nitrogen fixation, however, depends on the economic conditions and is in the line of decreasing cost of production wherever possible. Electric power is not available cheaply enough to make the arc process a likely competitor of the other processes. The synthesis of ammonia is developing most rapidly at present.

The great development in small rectifiers of the electrolytic type which was noted several years ago in the radio field has been checked by the recent

development of a-c. radio sets and the so-called dry or electronic rectifiers. Valuable information as to the details of improvements made in the aluminum rectifier as well as other types have become available. Mechanical rectifiers for high-voltage alternating current have been displaced by the vacuum tube.

In the field of electrochemistry of gases, outstanding developments are largely the researches of Dr. Lind and his associates who have been able to produce reactions at low temperatures without use of high voltages by exposing the gases to the emanations from radium. Similar work has been done by Daniels and others on the synthesis of ozone and nitric oxide by the use of high-voltage cathode rays. The use of ozone for the purification of drinking water has trebled within the past few years.

Outlets for electrical energy in various industries that have not previously made extended use of electricity are significant. In the paint, varnish, and lacquer industries the electrolytic production of lead carbonate is increasing. The synthetic preparation of acetic acid, acetone, and methyl alcohol in which electrolysis may play a part, has had an important effect in replacing products formerly obtained by wood distillation.

The heavy clay industry has made progress in the use of electrical machinery but is still behind in the development of such lines. Brick manufacturers are beginning to realize the advantages of electricity as a means of saving labor and the proper control of the products.

On all sides we find a constantly increasing demand for new products to meet conditions which were unknown in the past. Everywhere there is an increasing interest in the work of the research laboratories and the demand for greater results from research people.

The committee wishes to acknowledge valuable suggestions for the preparation of this report which have been made by Prof. C. G. Fink, secretary of the American Electrochemical Society.

GEORGE W. VINAL, *Chairman.*

Electrical Machinery

ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY*

To the Board of Directors:

At the beginning of this year, the Electrical Machinery Committee adopted a new plan of organization, comprising apparatus subcommittees to deal with matters in their respective fields, and, in addition, two general subcommittees, one responsible for the preparation of the annual report and the other responsible for the review of papers submitted to the Institute.

Each apparatus subcommittee has dealt with such matters as the initiation of papers, collection of information for use in the annual report, the development and publication of useful information, and the initiation and preparation of Institute standards in cooperation with the Institute Standards Committee.

Five apparatus committees have been organized during the year as follows: Transformer with W. M. Dann, Chairman; Synchronous Machinery, W. J. Foster, Chairman; Induction Motors, P. L. Alger, Chairman; D-c. Generators and Motors, A. M. MacCutcheon, Chairman; Mercury Arc Rectifiers, B. G. Jamieson, Chairman.

The chairman of each subcommittee has organized a committee whose membership has included members from the Electrical Machinery Committee and members from the Institute at large. While the membership of the Electrical Machinery Committee has been somewhat smaller than in previous years, there has been no limit placed upon the size of the several apparatus subcommittees. Each chairman has changed and increased the membership of his subcommittee as the nature of the work to be done has changed and increased.

The general committee on the annual report has consisted of C. W. Kincaid, chairman, and the chairmen of the various subcommittees. While the chairman of the annual report subcommittee has been responsible for the preparation of the annual report, he has looked to the chairmen of the several apparatus subcommittees for material within their respective fields.

The general subcommittee on meetings and papers has been headed by the chairman of the main committee, and he has called upon the entire membership of the committee for help in reviewing papers submitted by the Institute's Meetings and Papers Committee.

*ELECTRICAL MACHINERY:

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W. W. Spratt, Secretary, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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P. L. Alger,	C. M. Gilt,	A. M. MacCutcheon,
B. F. Bailey,	H. M. Hobart,	V. M. Montsinger,
B. L. Barns,	B. G. Jamieson,	E. C. Stone,
W. M. Dann,	A. H. Kehoe,	R. B. Williamson.
	C. W. Kincaid,	

Presented at the Annual Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

According to this plan of organization, the work of the committee has been subdivided among the various subcommittees, and whatever has been accomplished by the Electrical Machinery Committee has been due to the initiative, sense of responsibility, and hard work of the subcommittee chairman. The chairman of the main committee wishes to take this opportunity of acknowledging the value of its work and expressing his appreciation of the large measure of responsibility they have assumed.

The committee has held two general meetings during the year—one in October and another in February during the Winter Convention. In addition to these general meetings, the various subcommittees have held separate meetings as required by their programs. In general, the detail active work of the committee has been accomplished through the meetings and other activities of the subcommittees.

The transformer subcommittee under the chairmanship of W. M. Dann has completed very important work in connection with transformer standards. An appendix to Transformer Standards, Section 13 of the Institute Standards, has been agreed upon and submitted to the A. I. E. E. Standards Committee for their consideration and action. This appendix covers recommendations for the *operation* of transformers by total observable temperature, and permits the operation of transformers at loads greater than the rated load providing the temperature of the cooling medium is below 30 deg. for air or 25 deg. for water.

The transformer subcommittee has also had in preparation recommendations for standards of constant-current transformers. This work has been done under the immediate direction of H. C. Louis.

The synchronous machinery subcommittee, under the chairmanship of W. J. Foster, has cooperated with the Institute's Standards Committee and with the Sectional Committee of the A. E. S. C. in the revision of Section No. 7 of the Institute Standards. This subcommittee has in preparation recommendations for standards on capacitators.

The subcommittee on mercury arc rectifiers, B. G. Jamieson, chairman, has been particularly active in initiating standards for this new type of apparatus and in collecting information concerning the application and operation of rectifiers in this country and in Europe.

During the year, 17 papers have been presented under the auspices of this committee at the general and regional meetings of the Institute. These papers and the discussions resulting therefrom have made valuable contribution to design information on such subjects as the reactance of synchronous machines, turbine generators, magnetic leakage and fringing flux, elimi-

nating corona around armature coils of high-voltage machinery, methods of measuring cooling air, heat losses in the conductors of d-c. machines, excitation systems, and to the application information of two-pole synchronous motors, large frequency changers, etc.

The following review of progress during the past year has been prepared by the various subcommittees having jurisdiction over the particular machinery involved under the general direction of C. W. Kincaid. An attempt has been made in this report to include the more important articles that have appeared in domestic and foreign journals. These appear in several bibliographies and there are undoubtedly articles of real merit which have been overlooked. The committee will welcome having such omissions brought to its attention. A new plan has been initiated in connection with the bibliography in this annual report. It has been the endeavor to include all important articles and papers published during the calendar year of 1927 and, in addition, the outstanding papers that have been published in 1928 up to the time of publication. Next year's report will give a complete bibliography for 1928, repeating the more important references included in this report. By this plan the complete bibliography will be for calendar years (thus agreeing, as to dates, with the bibliographies prepared by leading libraries) and in addition, recent important articles and papers will be included.

Transformers

Very few engineers, with the exception of those intimately connected with the design of transformers, realize the remarkable changes that have been made in the design requirements during the last five years. With this in mind, we attempt to review in this report the factors that have brought about these changes and to show their effect on the developments of the past year.

These factors have been brought about by the natural growth and the changing requirements of the electrical industry which are due to the increase in capacity of power plants and substations, the extension of high-voltage transmission to higher voltage and greater power concentration, and the development of what can be properly termed high-voltage distribution networks.

These changes are responsible for the further development of the load ratio control transformer, the multi-winding transformer, and the varied winding auto-transformer. Such a unit not only steps up and steps down the voltage, but is frequently the meeting point of three or four voltages on the network, thus requiring three or four windings instead of two. Modern conditions also require that the voltages on various parts of a network be varied with the load. Thus it is no longer correct to speak of a "static" transformer. Gears, tap changers, and interlocking and remote control devices have been added for giving out and taking up the voltage slack of the system automatically as the load requires.

Then, too, the high-voltage distribution has resulted in many transformers with secondary windings of relatively high voltages. The 33-kv. secondaries have been quite common for some years. Now 66-kv. secondaries are often called for. Units are being built for 132 or 220-kv. to 66-kv. Even 110-kv. secondaries are appearing, and a bank with 140 kv. on both primary and secondary with load ratio has been built. This condition of having both windings at high voltages, of course adds to the physical size of a unit for a given kv-a. and since taps are frequently required in the secondary winding, they add to the difficulty of designing the unit.

There is one other factor that is of sufficient importance to mention. This high-voltage distribution with its increase in length of feeders has resulted in requirements for greater tap range in voltage due to the higher reactance of the feeders. Thus the customary 10 per cent range in voltage is no longer adequate for every condition, and tap ranges from 15 per cent to 20 per cent are being specified by some operators. This requirement adds to the size of the transformer and unbalances the design for it is practically impossible to maintain a balanced arrangement of the windings with respect to one another, except on one voltage connection. The unbalance increases with the tap range. Thus the larger the tap range, the greater the unbalance, the greater the change in reactance, and the greater the increase in short circuit forces.

Equipment for Changing Taps Under Load

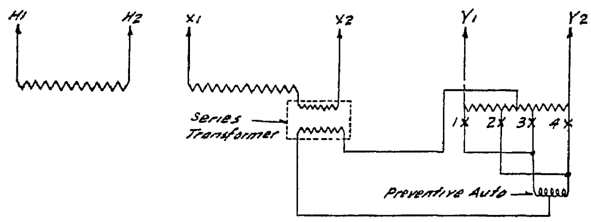
The report for 1926 describes in detail two methods of tap changing under load; namely, the two winding and the single winding arrangements.

During the year 1927, a large number of power transformers has been supplied with equipment for changing taps under load, with the ratio of the transformers changed by changing the voltage of a series transformer excited from a third winding on the core of the power transformers. This method permits the application of low-voltage tap changing equipment to high-voltage delta-connected windings and to high-voltage star-connected windings which are not grounded or to be grounded through a resistance.

Fig. 1 is a typical diagram of connections for this method of tap changing. A series transformer is connected in series with the winding whose voltage is to be regulated. One side of the primary of the series transformer is connected to the midpoint of the regulating winding, the other side of the primary winding being switched along the taps of the regulating winding by means of the tap-changing equipment. The familiar single-winding method is used for changing taps of the regulating winding. When power transformers are supplied with a third low-voltage winding for power purposes, taps can be placed on this third winding for use with the tap changer at only slight additional expense.

Three of the 10,000-kv-a. transformers shown in

Fig. 2 are used in a bank to transform 30,000 kv-a. from 140,000 to 140,000 volts, with equipment on one side for changing taps under load. Oil-immersed contactor switches are used to change taps by the single-winding method. Since the high-voltage winding whose voltage



SEQUENCE OF TAP CHANGING								
	Positions	1	2	3	4	5	6	7
Circuit	1	O	O					
Breaker	2		O	O	O			
	3				O	O	O	
	4						O	O

Fig. 1—Schematic Diagram of Connections for Changing Taps Under Load, Using a Series Transformer in the Winding whose Voltage is to be Changed and the Regulating Winding is a Third Winding on the Same Transformer

is regulated is connected in delta, a series transformer is connected inside the delta and is excited from a low-voltage tertiary winding. The tap-changing equipment is placed in the low-voltage winding.

What is thought to be the world's largest self-cooled

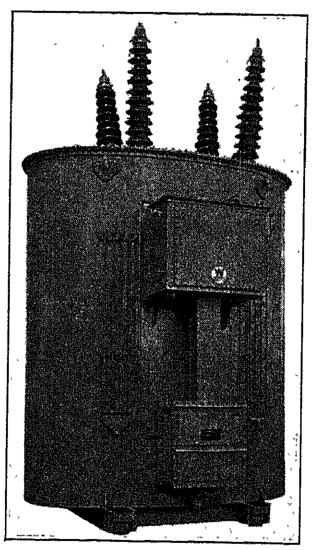


Fig. 2—10,000-Kv-a. Power Transformer—60 Cycle—Single-phase—140,000/140,000 Volts, with Load Ratio Control Equipment Mounted on the Side. Connections as Shown in Fig. 1, with Oil Immersed Contactors are Used

transformer has recently been completed. It is rated at 33,333 kv-a., 220,000 volts star, to 69,000 volts star, to 13,200 volts delta. Seven of these units (one a spare) will be used to form two 100,000 kv-a. transformer banks at the Plymouth Meeting substation of the Philadelphia Electric Co. Power generated at the new Conowingo hydroelectric plant will be stepped down from 220,000 volts through these banks for transmission through the present 69,000-volt Philadelphia system. The 13,200-volt windings will supply two 44,000-kv-a. synchronous condensers for line regulation.

These transformers while rated at 100,000 kv-a. per bank have three separate windings, with equivalent parts somewhat higher. With auxiliary cooling on the radiators, which is contemplated in the future, the equivalent two-winding loading which the transformers will deliver with low ambient temperatures is 200,000 kv-a. per bank.

Each transformer complete with oil weighs 180 tons and occupies approximately 500 sq. ft. of floor space. Some idea of the height of the tank is obtained by the fact that a six foot man can stand underneath the fourteen foot radiators as they are mounted on the tank. The height over the high-voltage bushing is 31 ft.

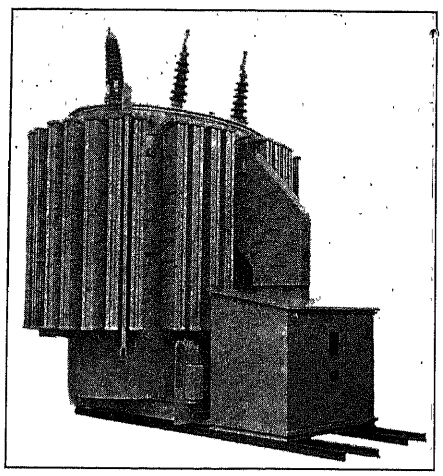


Fig. 3—33,333-Kv-a. Power Transformer—60 Cycle—Single-phase—220/69/13.2 Kv. with Load Ratio Control for the 69-Kv. Winding

The construction used made it possible to ship the transformers in oil to their destination, notwithstanding the large capacity and high voltage.

These transformers are provided with equipment for changing the voltage ratio of the middle voltage winding by means of tap-changing equipment located in the low-voltage winding. Only one extra tap is necessary for the tap-changing equipment, as the low-voltage taps, which are used for the starting of the synchronous condensers are used for the tap-changing equipment. The single-winding method of tap-changing is used, with a type *UB* tap changer and preventive auto-transformer and series transformer. The preventive auto-transformer is switched along the low-voltage taps by means of the circuit breakers of the type *UB* tap changer. The midpoint of the preventive auto-transformer and the midpoint of the low-voltage winding are connected to the primary of the series transformer, the secondary of the series transformer being connected in

series with the middle-voltage winding to give a voltage regulation of 15 per cent in six 2½ per cent steps. Fig. 3 shows this transformer and equipment.

Fig. 4 shows a 10,000-kv-a., single-phase, 35,000-volt transformer arranged for 20 per cent regulation, using a new type of tap changer of the single-winding

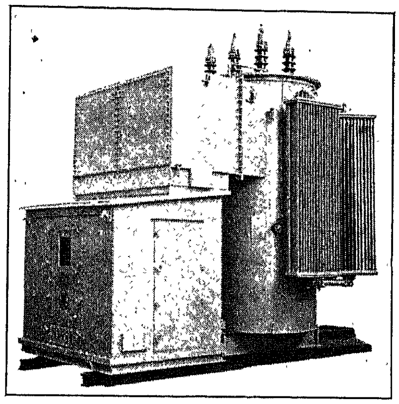
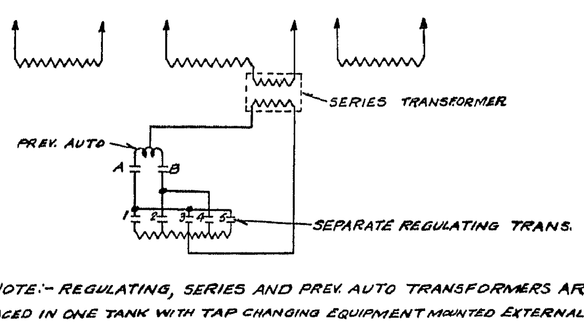


Fig. 4—10,000-Kv-a. Power Transformer—60 Cycle—Single-phase—35,000 Volt, with Control for 20 Per Cent Voltage Regulation, Using the Scheme of Connections Shown in Fig. 5

method. Fig. 5 shows the scheme of connections in which the series transformer is connected in the line to be regulated and the primary of the transformer is excited from a low-voltage winding which in turn may



SEQUENCE OF TAP CHANGING										
POSITION	1	2	3	4	5	6	7	8	9	
SWITCH-1	O	O								
2		O	O	O						
3				O	O	O				
4						O	O	O		
5								O	O	
CIRCUIT A	O	O		O	O	O		O	O	
BREAKER B		O	O	O		O	O	O		

O CIRCUIT BREAKER AND SWITCH CLOSED

Fig. 5—Schematic Diagram of Connections for Changing Taps Under Load Using a Series Transformer and a Regulating Winding, both of which May be in the Same Winding

be excited from any of the transformer windings. Only two tap-changing circuit breakers are used, an auxiliary oil-immersed tap-changing switch being used to do the actual tap-changing. One of these transformers is arranged for complete automatic control in response to fluctuation of the system voltage.

Fig. 6 shows tap-changing equipment applied to ten 20,000-kv-a., three-winding transformers by means of separate regulating units. The regulating transformer, which is excited from the low-voltage winding of the main transformer, and the series transformer are mounted in a separate tank to which the tap-changing equipment is attached.

Another interesting development is a 6850-kv-a.,

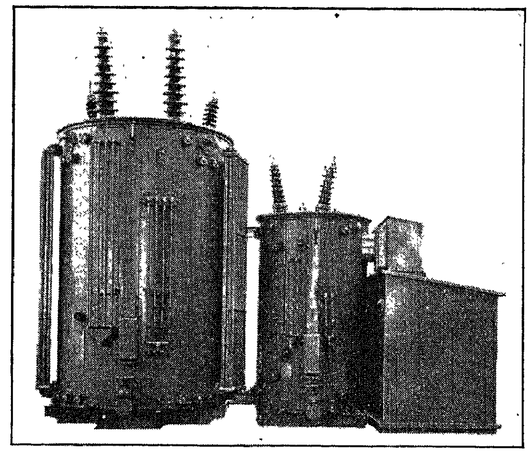


Fig. 6—20,000-Kv-a. Three Winding Power Transformer with the Series Transformer and Regulating Transformer Mounted in a Separate Tank to Which the Tap-Changing Equipment is Attached

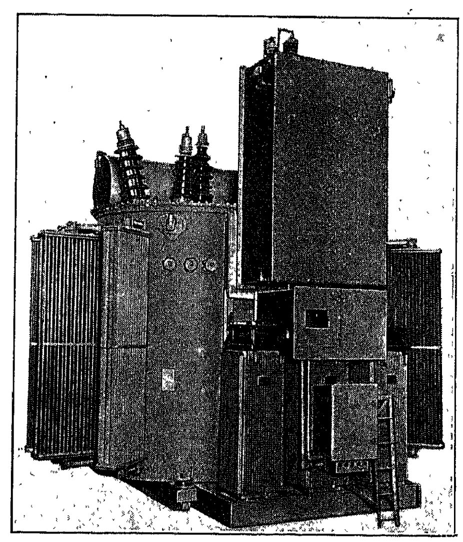


Fig. 7—6850-Kv-a. Three-phase Power Transformer 66,000/60,000 Volts with 43 Per Cent Voltage Regulation by Means of Taps and Induction Regulators

three-phase, O. I. S. C. 66,000- to 60,000-volt transformer with type *UR* tap-changing equipment to give 43 per cent voltage regulation under load. Three 60-kv-a., single-phase induction regulators are stepped across taps of the transformer to give smooth curve voltage regulation over the entire range with an infinite number of operating voltage positions. A three-phase induction regulator to cover the same range would have to have a capacity of 1400 kv-a. The equipment is so

designed to be applicable to larger kv-a. transformers merely by the substitution of larger kv-a. regulators, and is built for future addition of automatic control which is responsive to voltage fluctuations of the system. Fig. 7.

The Inertaire Transformer

In addition to the 33,333-kv-a. transformers for Philadelphia Electric Co., four 33,333-kv-a., O. I. S. C.

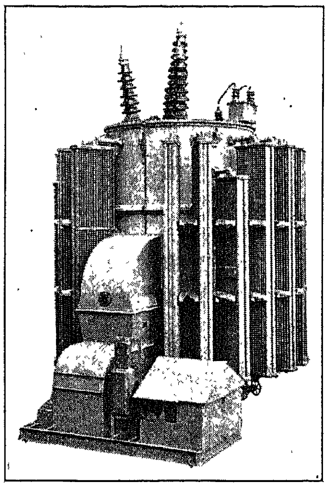


Fig. 8—33,333-Kv-a. Inertaire Power Transformer 220,000/16,500 Volts, 50 Cycles. Equipped with Auxiliary Air Cooling on the Radiators

Inertaire transformers for Southern California Edison Co. have been built. These transformers will be installed in a 100,000-kv-a. bank, with a spare, at Long Beach Steam Plant No. 3, to operate on a 220-kv., three-phase, 50-cycle system transforming from this voltage to 16,500 volts on the low-voltage winding.

These transformers are two-winding units arranged with detachable radiators equipped with duct for air blast. Complete with blower equipment these units will each weigh approximately 98 tons and occupy a floor space of 360 ft. Over-all height from rail to bushing tip, approximately 32 ft. They will carry 60 per cent normal load continuously with an ambient of 40 deg. cent. without exceeding 55 deg. cent. when the blowers are not in operation. Blowing equipment is individual and mounted on separate base with wheels. By opening the duct at one point, complete blower equipment can readily be moved away from the main units.

The motors for this equipment are of the across-the-line starting characteristics. All motors, including spare unit, are arranged to be started and stopped together by relay actuated by temperature conditions inside the main transformer. These transformers are shown in Fig. 8.

In the Inertaire transformer, the breathing regulator allows in-breathing at a slight vacuum but prevents out-breathing until a pressure of 5 lb. is developed in the transformer tank. Thus there is a definite relation between the amount of initial gas space required and the change in oil volume to keep the transformer from breathing.

With small transformers this relation can be obtained with a reasonable initial gas space, but as the size of the transformer increases, with its consequent reduction in gradient between copper and oil, it becomes desirable to decrease the amount of breathing by providing additional gas space to supplement the volume above the oil level.

During the past year it has become customary to supply on all large transformers some additional gas space other than that above the oil, in order to cut down the amount of breathing of the transformer. This decrease in breathing reduces considerably the cost of maintenance of the Inertaire equipment for the chemicals of the Inertaire jars are used up in proportion to the amount of breathing which takes place.

Several methods are used to obtain this additional gas space.

The general practise, as shown in Fig. 9, is to place gas chambers beneath the oil level between the iron core and the tank. These are crescent-shaped compartments welded to the tank wall with or without a space between, depending upon the type of transformer. In a few cases ordinary expansion tanks have been supplied, filled with an inert gas and connected to the gas space in the transformer tank. These act as gas chambers and cut the breathing of the transformer down to a minimum. Another type of gas chamber consists of connecting a spare tank to the gas space of one or more transformers, and this auxiliary space provides the necessary gas space to prevent the transformer from breathing. In this way the maintenance cost of the

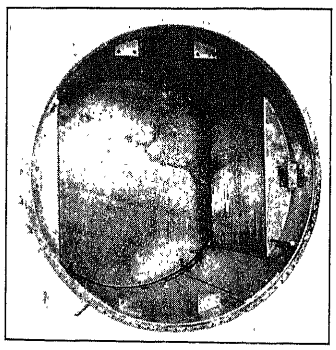


Fig. 9—Internal Tanks to Provide more Space for Expansion of Inertaire and thus Reduce the Amount of Breathing

Inertaire transformer in extremely large sizes which ordinarily breathe large volumes of air has been greatly reduced.

There are approximately 85 different operating companies now using Inertaire transformers, with a total Inertaire transformer capacity of about 5.5 million kv-a. in service.

Distributing Transformers

During 1927 a number of three-phase, 60-cycle, O. I. S. C. manhole transformers of 300- and 450-kv-a. capacity were built. These transformers take power at approximately 11,000 volts, delta, and supply the low-voltage network at 199 volts star with a permanently grounded neutral for four-wire operation.

Each transformer is fitted with the usual thermometer, oil-gage, drain, filter and sampling valves, and in addition, due to the possibility of vaults or manholes being flooded with water, each transformer is fitted with a high-voltage and low-voltage pothead to which lead-covered entrance cables can be attached. A three-phase tap changer in the high-voltage winding is also used and controlled by a single hand-lever, operated outside of the tank. In addition, the high-voltage side of the transformer is fitted with a three-way disconnect and grounding switch such that the high-voltage line can be open or it can be connected to the transformer or solidly grounded for protection when necessary to do any work on the unit. This switch is operated outside of the tank and can be padlocked in each position. Inside the tank is an electrical interlock

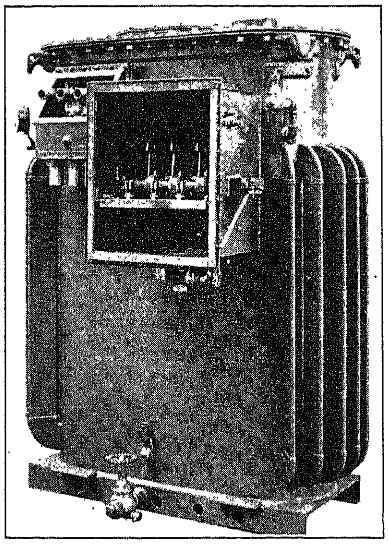


Fig. 10—Three-phase Network Transformer Equipped with Junction Boxes and Cable Disconnecting and Grounding Switch in Primary Junction Box. Junction Boxes Open. Switch in Operating Position

which automatically locks this switch when the transformer is energized.

An all-welded boiler-iron tubular tank is used with the high-voltage and low-voltage potheads made as an integral part of the tank. Each tank has a structural steel base to facilitate any moving of the transformer during installation. Lifting eyes are provided to handle the complete transformer. (Fig. 10.)

Current Transformers with Nickel-Iron Cores

The errors in a current transformer are due to the characteristics of the core material used. When this material has high losses and low permeabilities, the errors will be much larger than when the material has low losses and high permeabilities. Research work has resulted in the development of a new magnetic material called Hipernik which possesses exceptionally low losses and high permeabilities.

By the further development of a special magnetic circuit, which permits fuller use of the exceptional qualities of Hipernik, current transformers have been developed in which the errors are practically negligible, and far less than heretofore possible to make them using

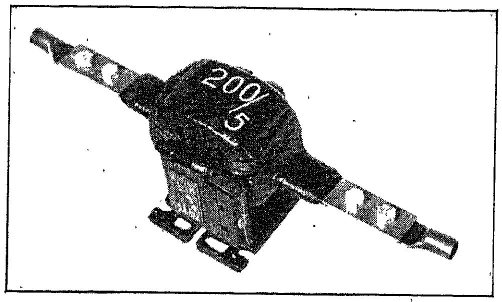


Fig. 11—Precision Current Transformer Using Hypernik Steel

silicon steel. The application of these transformers is not confined to any particular class of secondary burdens, but may be used with any type of secondary burden within the rating of the transformer. Fig. 11 shows the appearance of one type of transformer developed.

Some current transformer units for use on 154,000-volt circuits were built during 1927. These are, so far as is known, the highest voltage instrument current transformers ever produced. Fig. 12 shows an interior view of one of these units.

The voltage limit in potential transformers was carried to a new figure in the manufacture of some units built for operating on a 220-kv. system in the East. Fig. 13 shows an external view of one of these transformers.

A New Testing Outfit for Insulating Oils

The importance of keeping a careful check on the dielectric strength of oil used for insulation purposes is readily recognized. In most testing sets the variable high voltage necessary for testing oil is secured by switching a low voltage between taps on the primary side of the transformer. This method requires that the transformer be deenergized and then reenergized between taps. Such a method introduces distortions in the test voltage which lead to erroneous interpretation of the oil failure. A new method in which the transformer is energized at all times during an oil test has been devised and incorporated in a testing set shown in Fig. 14. In this set, the test voltage can be raised fairly smoothly without the introduction of transients;

hence, the voltage observed from the meter is a correct indication of the voltage at which the oil was tested.

The complete set is arranged in an aluminum case and can be carried in the same manner as a suitcase. It operates from an ordinary light socket at 110 volts, 60 cycles.

The a-c. high-voltage testing sets furnished during the year included complete equipment for several new laboratories. There were transformers, each rated 60 cycles, 300/600 kv-a., 250,000 to 1150/2300 volts and designed for chain connection to give 750,000 volts to ground. Individually, they are guaranteed for continuous operation and so far as known are the highest voltage units ever built for such service.

For use in making commercial tests on cables, there were built some 400-kv-a., 200,000-volt transformers, two of which were arranged in series to give 400,000 volts to ground.

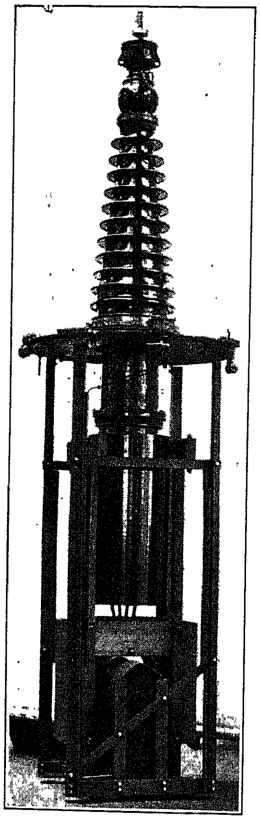


Fig. 12—Instrument Current Transformer for 155,000-Volt Circuit. 200/400 Amperes

One of the most complicated little testing transformers ever designed is one rated 60 cycles, 1.5 kv-a., 5010 to 110/220 volts, shown in Fig. 15. The high-voltage winding is so arranged that practically any voltage between 2 and 5010 may be obtained. Low reactance was specified and the measured impedance was 0.244 per cent.

D-c. Kenotron Testing Sets

Two 400,000-volt sets, placed in service during the past year, gave the highest d-c. voltage so far used in commercial work. One of these installations is shown in Fig. 16.

There were several new equipments developed during the year, one, a 7500-volt set illustrated by Fig. 17, is unique in that it will be used for tests on 600-volt d-c. distribution feeders, a new application.

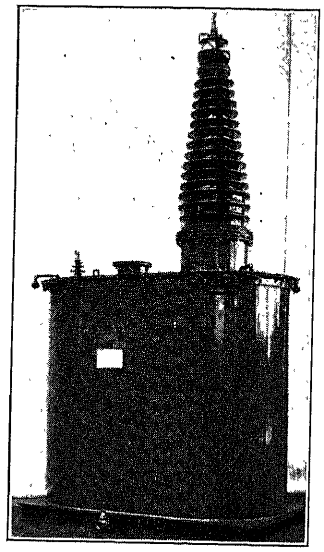


Fig. 13—Instrument Potential Transformer for 220,000-Volt Grounded Circuit

Cable Entrance Junction Box Transformers

The development of higher-voltage cables, the desire of operators to avoid exposed connections, and especially the difficulty of making satisfactory end-bells, led to the adoption of transformers with cable entrances—the cable either terminating directly inside the transformer tank, or terminating in oil or compound-filled junction boxes which are connected to the transformer

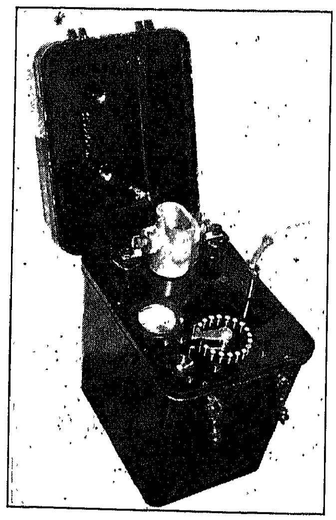


Fig. 14—Portable Testing Outfit for Checking the Quality of Transformer Oils

by means of bushings, both ends of which are immersed in oil.

Frequently, the necessity for routine testing of the

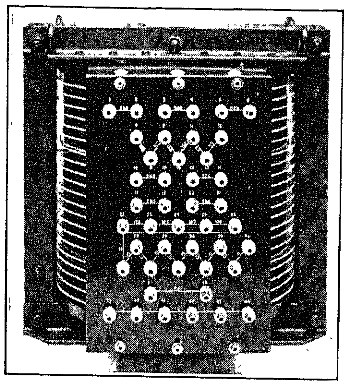


FIG. 15—LABORATORY VARIABLE RATIO TRANSFORMER, 1.5/5010 VOLTS

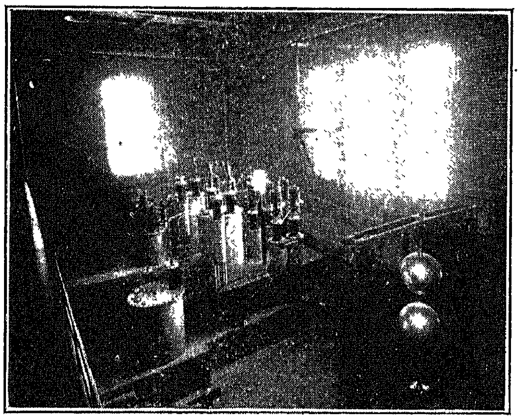


FIG. 16—INSTALLATION OF 400,000-VOLT D-C. CABLE TESTING SET

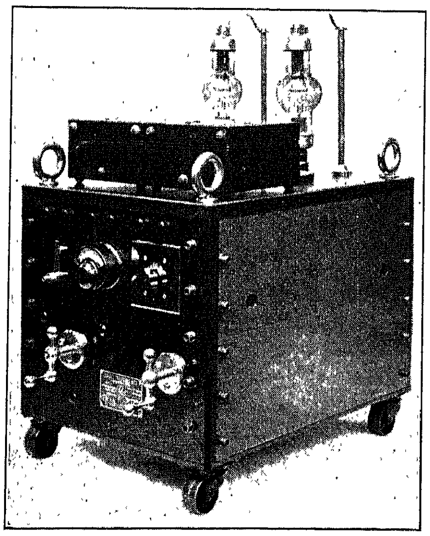


FIG. 17—D-C. CABLE TESTING SET. 7500 VOLTS END GROUNDED

cable requires means of readily disconnecting the cable from the transformer. To an increasing extent, disconnecting switches are fitted in the junction boxes with special testing bushings, so that the cable can be switched from the transformer to the testing connection or to the ground. Fig. 18 shows an installation of such transformers.

A notable example of the adoption of this means of protection is found in the group of 20,000-kv-a., water-cooled transformers, furnished by one manufacturing company for the State Line Generating Company. These consist of 17 single-phase and 4 three-phase units, all of which receive current from the generator at 22,000 volts. The high-voltage ratings of seven of the single-phase units is 132,000 Y, the remaining ten being 66,000 Y, and three-phase units 33,000 Y. All these transformers are provided with cable-entrance bushings on the low-voltage side and all but the 132,000-volt

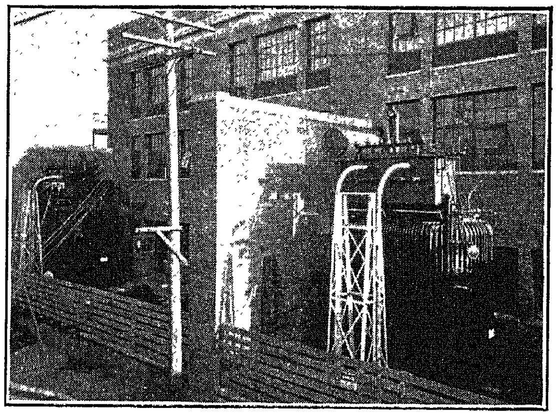


FIG. 18—INSTALLATION OF POTHEAD TRANSFORMERS WHICH COMBINE THE CABLE POTHEAD WITH THE TOP OF THE TRANSFORMER

units are equipped with cable-entrance bushings and self-contained disconnected switches on the high-voltage side. These transformers are also provided with load ratio control.

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SYNCHRONOUS MACHINES

The tendency toward larger machines in certain lines continued throughout the year 1927. This was true especially in connection with steam turbine generators, the sizes of which went up in erratic steps to 160,000 kw. for a single-shaft unit, and to 208,000 kw. for a three-shaft unit.

The trend in mechanical design was away from castings, so generally employed heretofore, since the first electrical machines were made, to the use of fabricated structures for practically all parts of the machine. These structures are made by welding together standard plates and standard structural shapes, such as beams, channels, and angles.

The trend in electrical design has been toward all possible reduction of losses and, consequently, attainments of higher efficiencies. The attack has been made, for the most part, on load losses, especially the losses in the mechanical parts due to stray fluxes.

Considerable thought has been given to the matter of improving the stability of machines by quick response excitation and superexcitation. A number of installations of such systems of excitation were in contemplation at the end of the year. Investigations and tests in the shops of various manufacturers were carried on.

HYDRAULIC GENERATORS

There has been an increasing number of installations where automatic operation or distant control has been introduced.

Outdoor installation of hydraulic generators was often under consideration, but no important installation was made during the year.

Great interest was shown during the year in the progress of the Conowingo Development on the Susquehanna River in the State of Maryland, under the direction of Stone & Webster, for the Philadelphia Electric Company, owners of the plant. The Annual Report of the Electrical Machinery Committee for 1926-27 gives considerable data on the generators, which are 40,000 kv-a., 81.8 rev. per min., 13,800-volt, 60-cycle machines. The present development consists of seven units; see Fig. 19, assembly in cross section of the combined wheel and generator. Six of these units were in operation June 1, 1928.

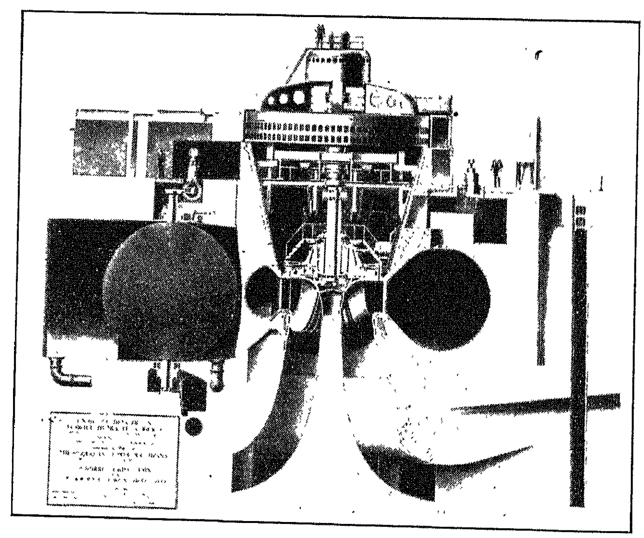

FIG. 19—SECTION THROUGH 40,000-KV-A. VERTICAL WATER-WHEEL GENERATOR AND TURBINE

Both manufacturers introduced fabricated steel plate structures, but one of them used it to a greater extent. Practically the only parts of its machine that were made of castings are the upper bearing bracket and the hub of the rotor. Probably the most interesting and novel part of this generator is the rotor spider. Views of plate rim and arms are shown in Figs. 20 and 21.

At the close of the year one manufacturer reported a list of large hydraulic generators that had been put into operation, or had been made in its shops, or for which orders had been received during the year as follows:

2–45,000-kv-a., 50-cycle, 11,000-volt, 250-rev. per min. horizontal generators are the largest of their type yet undertaken;
4–29,000-kv-a., 12,000-volt, 60-cycle, 100-rev. per min. vertical generators, with direct-connected auxiliary generators which supply power for motor-generator exciter sets arranged for quick response excitation;
2–45,000-kv-a., 13,800-volt, 60-cycle, 400-rev. per min. vertical generators, with direct-connected exciter and pilot exciter;
2–45,000-kv-a., 13,200-volt, 60-cycle, 150-rev. per min. vertical generators;
2–22,500 kv-a., 60-cycle, 6600-volt, 120-rev. per min. vertical generators, with direct-connected exciters;
2–28,000-kv-a., 50-cycle, 11,000-volt, 300-rev. per min. vertical generators, with direct-connected exciters.

Another manufacturer reported installation and putting into service during the year two plants where

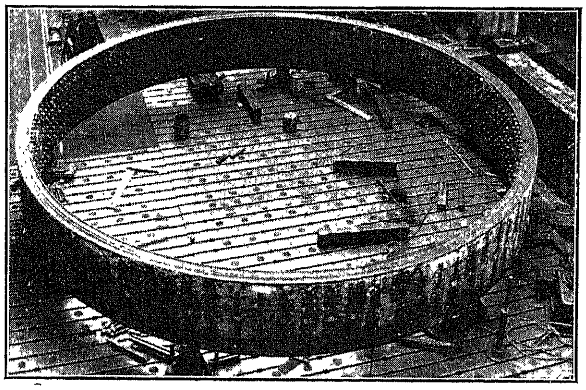

Fig. 20—Assembled Rotor Run for 40,000 Kv-a. Conowingo Generator

the closed systems of ventilation were introduced. One of these is the low-head plant of the Louisville Gas & Electric Company on the Ohio River, which contains eight 12,550-kv-a. vertical 60-cycle generators running at 100 rev. per min., arranged for remote control. See Fig. 22. The other plant is that of the Washington Water Power Company, Lake Chelan, Wash., containing two 30,000-kv-a., 300 rev. per min., 60-cycle vertical units, the first one of which was put on the line during the fall.

The scheme of circulation of air is practically the same in the two plants. Eight water coolers are assembled at approximately equal intervals around the circumference, and arranged in pairs for circulating the air. In case of the smaller and lower-speed generator, all of the air passes into the pit underneath the generator and is driven out through the stator cores and windings by fans on the rotor, passing into the several sections of the stator frame and through the coolers, dropping down into conduits leading back into the pit. Every pair of coolers has an outside housing attached to the stator frame. In case of the larger and higher-speed generator, the outside housing is continuous, making a complete circle outside the stator frame, but the air into and out of every pair of coolers divides, a part of it passing upward and returning into the rotor via one of the four air pipes that connect into a common air chamber surrounding the top of the machine, and

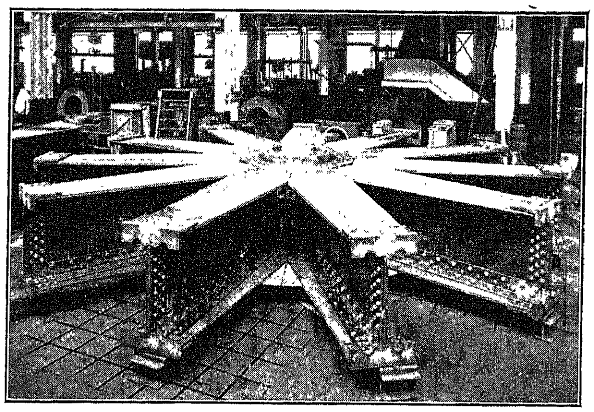

Fig. 21—Assembling Rotor Spider for Conowingo Generator

the rest of the air passes downward into conduits in the concrete foundation, and thence back into the rotor.

Steam Turbine Generators

Two or three European manufacturers of steam turbine units have designed or built 3000-rev. per min. generators with ratings as great as 37,500 or even 40,000 kv-a. The American manufacturers are more interested in 3600 rev. per min., or 60-cycle generators;

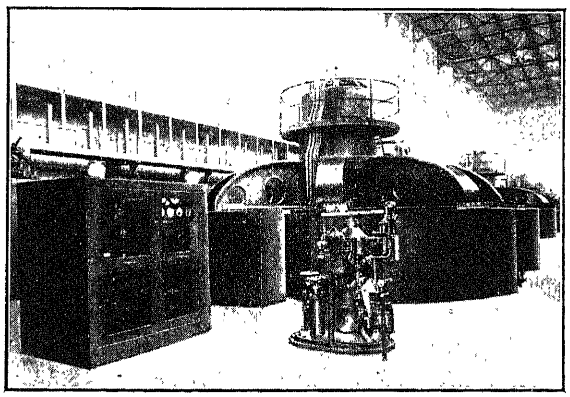

Fig. 22—Water-wheel Generators Showing Coolers Attached to Frame

12,500 kv-a. generators of this speed were made during the year and 15,625 kv-a. was designed.

The large 1800-rev. per min. generator mentioned in last year's report was installed and put in service during the year at Waukegan, Ill. It is rated 59,000 kv-a., 50,000 kw., 12,000 volts, and uses the closed system of ventilation with two external blowers and fin-type radiators. The operation of the generator has

been satisfactory, especially in respect to quiet running and low temperature in both rotor and stator.

Skeleton types of stator frame, consisting of steel plate, welded or riveted, in place of castings, have been quite generally designed and built, especially for the largest generators. This construction results in machines that are not so limited by shipping facilities.

Among the more noteworthy large generators in process of manufacture is the cross-compound 188,000-

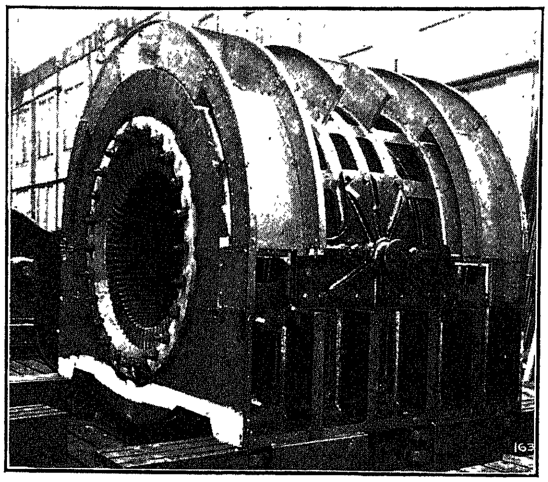

FIG. 23—TURBO GENERATOR STATOR WITH VENTILATING OUTER SKELETON PARTLY ASSEMBLED

kv-a. unit for the New York Edison Company, which consists of two 94,000-kv-a., 13,800-volt, 60-cycle, 1800-rev. per min. generators. These are the largest 1800-rev. per min. generators yet built. This unit is

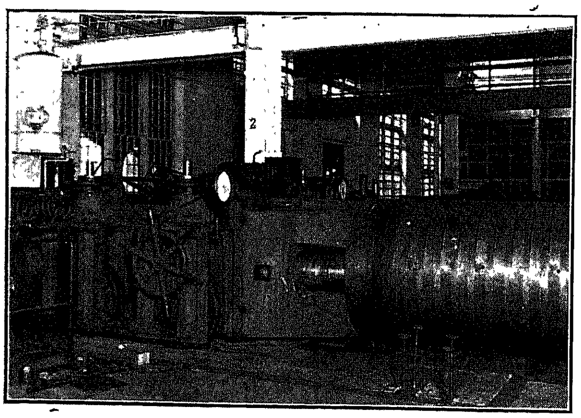

FIG. 24—HYDRAULIC BOLT PULLER FOR TIGHTENING THROUGH BOLTS IN PLATE TYPE TURBO ROTOR

of special interest in that the separately driven fans for supplying the cooling air are the vertical type driven by 3600-rev. per min. induction motors, three fans in all, mounted between the generators. The air is discharged from the top of the generators into a common chamber from which the fans take it and pass it through the coolers back into the generators.

This same company has extended the use of the skeleton stator frame to all large 1800-rev. per min. generators where shipping limitations require it. Fig. 23 shows a turbine generator with part of the superstructure installed.

This company has developed the plate rotor with forged shaft ends, and also has developed a hydraulic bolt puller for fastening together plates and shaft ends. A partial view of one of these rotors in the bolt-pulling machine is shown in Fig. 24. Two bolts can be pulled at the same time. The nuts are run on by hand after the plates are stretched, and this practise prevents thread friction and galling under the nuts. An improvement introduced during the year, in connection with built-up plate rotors, has been the making of the plates with holes in the center, in connection with which it has been found possible, by proper heat treatment, to raise the elastic limit on carbon plates from 23,000 to 55,000 lb.

During the year, the single-shaft generator units

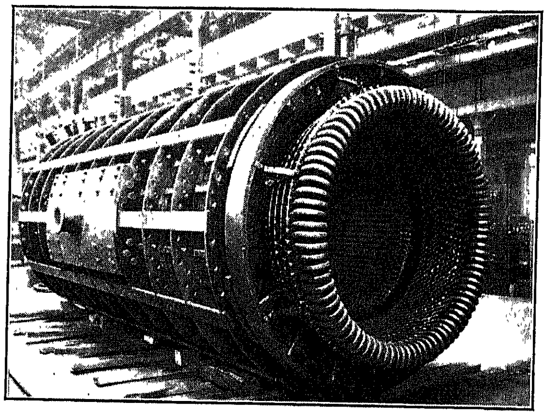

FIG. 25—INNER SKELETON STRUCTURAL FRAME FOR TURBO GENERATOR

put into service by another manufacturer are as follows:

75,000-kv-a., 0.8-p. f., 1800-rev. per min. generator in the Edgar Station of the Boston Electric Illuminating Company, with direct-connected house service generator of 6250 kv-a., 0.8 p. f.;

A 55,000-kv-a., 0.9-p. f., 1800-rev. per min. generator in St. Louis. This generator has fans on the rotor and is at the present time the largest self-ventilated machine at 1800 rev. per min. that this company has built.

The first of this company's 22,000-volt generators was completed. It is 61,765-kv-a., 0.85-p. f., 1800-rev. per min. with direct-connected house service generator of 3571-kv-a., 0.7 p. f. It is to be installed in the Powertown Plant of the Superpower Company of Illinois.

The first of the two 100,000-kv-a., 1500-rev. per min., 50-cycle generators for the Southern California Edison was practically completed at the end of the year. The wound stator is shown in Fig. 25, while the outer stator frame is shown in Fig. 26.

Other single-shaft units in process of manufacture at the close of the year were a 66,667-kv-a., 0.9-p. f., 1800-rev. per min., 60-cycle generator, an 83,333-kv-a.,

0.9-p. f., 1500-rev. per min., 25-cycle generator, and a 160,000-kv-a., unity power factor, 1500-rev. per min., 25-cycle generator. One of the features of the construction of the 160,000-kv-a. is the arranging of the stator winding as two entirely independent windings, each having capacity of 80,000 kv-a., connected through separate switches to adjacent bus sections. Two distinct advantages are to be obtained by this scheme; first, reduction in size of the individual switches; second, the elimination of bus reactors made possible by the transfer of power taking place through the coupling effect of the two separate windings.

In multiple-shaft units, it has nearly completed a 165,000-kv-a., consisting of three generators of practically the same rating for the American Gas & Electric Company, Philo Station. It also has begun work on a 208,000-kw. unit for the State Line Company consisting of one 89,412-kv-a. generator, and two 72,941-kv-a. generators, all at 1800 rev. per min. and wound for 22,000 volts.

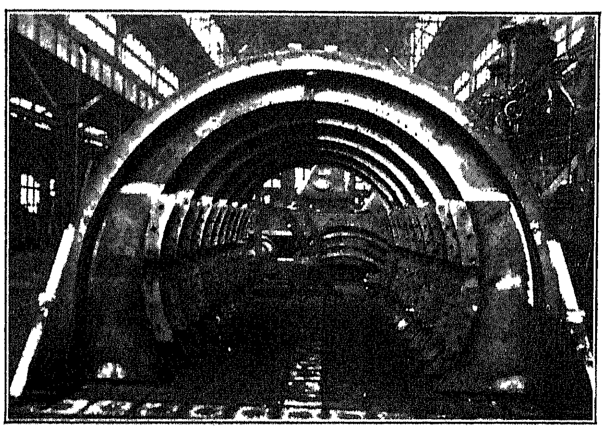

Fig. 26—Outer Skeleton Structural Frame for Turbo Generator in Fig. 25

The advantages secured by the use of skeleton frame construction were set forth somewhat in detail in last year's report. They appertain chiefly to the matter of shipment. It has been found possible to design all three of the large generators in the 208,000-kw. triple-shaft unit State Line, with skeleton type frames, so that they may be wound at the factory and shipped complete, no outer frame or superstructure being required.

An advantage obtained by designing the stator frame with inner and outer parts like those shown in the photographs pertaining to the 100,000-kv-a., is the facility with which such machine may be made fit to contain some gas other than air in its ventilation system. There will be involved simply the removal of the outer frame and the substitution of a gas-tight structure of welded steel plates.

Additional tests in an atmosphere of hydrogen have been conducted during the year on the 6250-kv-a. generator mentioned in last year's report.

Marine Turbine Generators

During 1927 the two airplane carriers,—the *Lexington* and the *Saratoga*, were put into commission. They are the largest electrically-equipped ships afloat. Each has four 40,000-kv-a., 1755-rev. per min., 5000-volt generators. The motors, direct-connected to the propellers, are induction motors.

During the year the *SS. California*, plying from New York to San Francisco via the Panama Canal, was equipped, with a 48-cycle steam turbine generator, and synchronous motors. The ship is a large one of slightly more than 30,000-tons' displacement. The two turbine generators are rated 6600 kw. each, at 48 cycles. The reversible synchronous motors are 8500-hp. each, at nominal speed of 100 rev. per min. The speed of the ship is to be 18 knots with both turbines running.

U. S. Coast Guard Cutters

The economy of the centralized power plant has been adapted to the machinery now being installed in five U. S. Coast Guard Cutters. The machinery consists of a main turbine generator rated 2600 kw., a 3000-hp. synchronous propelling motor, condensing equipment, and electrified auxiliaries. In addition are two dual-drive units, each consisting of a high-speed turbine and gear, a direct-current generator, and a synchronous machine that is used either as a generator or a motor. Under the usual condition of operation the power for a-c. auxiliaries is supplied direct by the main generator and for the d-c. auxiliaries from the same source through the dual-drive unit. By this method of using the main turbine generator to furnish power for auxiliaries the total steam consumption has been materially reduced. During maneuvering or when the main unit is secured, all auxiliary power is supplied by the dual-drive unit, driven by its turbine.

Synchronous Motors

An increasing demand for synchronous motors was in evidence during the year. Undoubtedly it is safe to say that they are now being applied in certain cases where induction motors were formerly thought necessary. They are being introduced into steel mills where they were not formerly considered.

There was a decided demand during the year for "full voltage" or "across-the-line" starting. This has probably resulted from the fact that better starting torque efficiency has been introduced into synchronous motors by more skilful design, and to the fact that the systems on which they operate have become larger, relatively, to the individual motor.

For applications where the starting requirements are most severe such as driving large grinders in cement mills, as a rule, salient-pole machines have been furnished, many of them with double squirrel-cage starting windings, some with magnetic clutches, and some of the so-called "supersynchronous" type. The last-named consists of a motor with a stator that may revolve,

and be brought up to synchronous speed with the rotor at rest, and with the clamps arranged to exert a braking effect on the stator to bring it to rest while the rotor comes up to full speed.

Another company has built during the year induction synchronous motors as large as 1500 hp. at 163 ⅓ rev. per min. Fig. 27 shows a 1500-hp. motor that has been in operation at the plant of the Atlas Cement Company. It starts like an induction motor with definite wound secondary and external resistance. After attaining rated speed, d-c. excitation at 50 to 60 volts is supplied from a small induction motor-driven set. Excitation required is, approximately, 500 amperes. It is to be noted that the windings in the rotor are much deeper than in an induction motor, since these windings serve as synchronous motor excitation windings.

Synchronous Condensers

Quiet operation has been emphasized in connection with the placing of orders for many of the synchronous

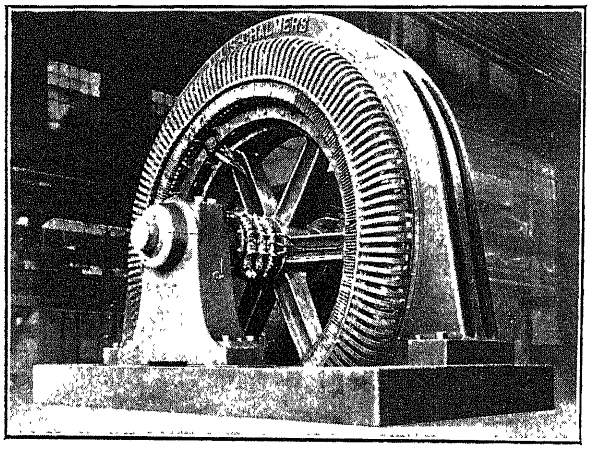

Fig. 27—1500-Hp. 163⅓-Rev. Per Min. Synchronous Motor for Use in Cement Mill

condensers built during the year. Two installations of 5000-kv-a., 750- or 900-rev. per min. condensers were made for the City of Los Angeles which were provided with the closed system of ventilation, containing radiator type of coolers mounted in the condenser foundation.

It is interesting to note that during the year two of the 50,000-kv-a. synchronous condensers for the Southern California Edison Company were put into operation in two substations in Los Angeles. These large condensers also had the closed system of ventilation with air coolers underneath. It is probable that the purchaser of these condensers specified this method of cooling not so much on account of the reduction in noise as because they were machines of very large capacity at high speed, and also for the reason that he wished to equip the substations with carbon dioxide gas, or some other fire-extinguishing compound.

A 7500-kv-a., 900-rev. per min., 60-cycle condenser was installed in Malden, Mass., and a 10,000-kv-a., 900-rev. per min. in Springfield, Mass., both with closed systems of ventilation and air coolers. The reduction of noise to a minimum was the consideration in both cases.

Two synchronous condensers to be installed outdoors, and for hydrogen operation, were in process of manufacture during the year. The smaller of these, 10,000-kv-a., when operating in air, and guaranteed to be at least 12,500 kv-a. when operating in hydrogen,

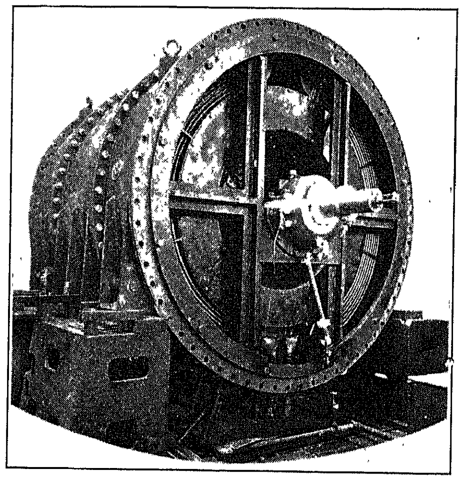

Fig. 28—Hydrogen Cooled Synchronous Condenser with End Bell Removed

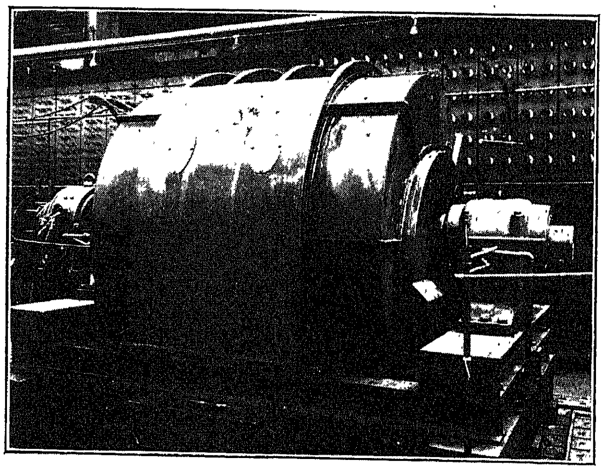

Fig. 29—7500-Kv-a. Synchronous Condenser Showing Structural Frame, End Bells, and Bedplate

was completed during the year, but not tested at the close of the year, except to be filled with the most explosive mixture of hydrogen and oxygen. It exploded in the explosion-proof pit. This was done to make sure that no damage would be done to the structural parts of the machine in case of an explosion. Fig. 28 shows this condenser in the testing pit, with head removed, revealing the coolers, which are semicircular in shape and arranged two at each end.

Most companies are now building the 5000-, 7500-, and 10,000-kv-a., 60-cycle condensers at 900 rev. per

min., instead of 720, thereby reducing weight, floor space required, and total losses.

Fig. 29 shows a 7500-kv-a. (condenser) with structural steel frame, end bells, base, sub-pedestals, etc.

Three 30,000-kv-a. condensers at 720 rev. per min. are now building for Philadelphia.

Frequency Converters

Nearly all frequency converter sets have synchronous machines at both ends. Probably the largest set of this type made during the year was a 29,400-kv-a., 25- to 60-cycle.

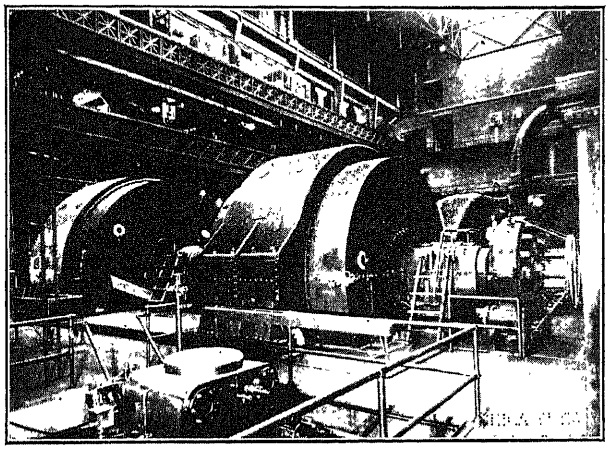

Fig. 30—21,400-Kv-a., 25-Cycle Single-phase Frequency Changer-Spring Mounted

In cases where some flexibility in the voltage-tie between two systems is desirable, induction frequency converters may well be used. Such need may arise in the operation of synchronous converters, some of them from one of the systems, and some from the other, that feed direct current into common lines. Such a condition exists in New York City where large induction frequency converter sets have already been installed. Orders were placed during the year for two more 40,000-kw. sets.

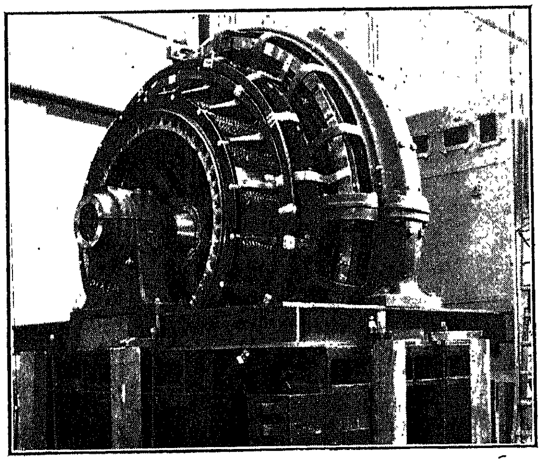

Fig. 31—4200-Kw., 25-Cycle Synchronous Converter

Fig. 30 shows a set rated 35,300 kv-a., three-phase, at the 60-cycle end, and 21,400 kv-a., single-phase, at the 25-cycle end, 13,600 volts. The 25-cycle end has a spring mounted stator frame. This set has been placed in operation in Philadelphia.

Orders have been placed for three 15,000-kw., 60- to 25-cycle sets for the same city. The rating of the 25-cycle, single-phase generator is to be 21,428 kv-a., 0.7 power factor. There have been furnished during the year two 60- to 25-cycle frequency changers for New Haven road, in which the 7140-kv-a., 25-cycle, single-phase generators had spring-mounted stators.

In certain cases, where the frequency converter serves as a tie between two systems, and is relatively small in comparison with the smaller of the two systems, Scherbius sets, or some equivalent that has flexibility in the frequency ratio, should be employed.

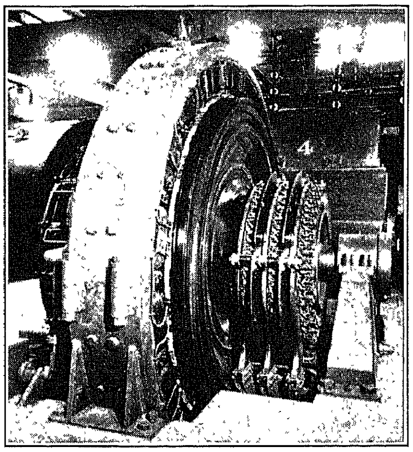

Fig. 32—4200-Kw., 25-Cycle Synchronous Converter. Using Bent Slab Frame and Roller Bearings

Two sets of this type were being installed at the end of the year and one was put in service in April. These sets are to connect the 25- and 60-cycle systems of the Niagara Lockport and Ontario Power Company and are the largest sets of this kind yet built. The set is rated 25,000 kv-a., 20,000 kw. on the synchronous machine end and the induction motor which is rated 28,000 hp., 95 per cent leading power factor has the the largest rating of any induction motor in operation.

Synchronous Converters

Fig. 31 shows the commutator end of one of the two 4200-kw., 25-cycle lighting type converters for Edison three-wire service that were built on a certain order. The voltage range is 240 to 300, obtained by combination of transformer tap changing and field control. The base is structural steel.

Fig. 32 shows the collector end of a converter of the same rating, 4200 kw. The construction shown is typical of the present practise of one manufacturer. It utilizes a bent steel slab magnet frame, steel lugs

welded on the sides to bolt the two halves together, and plate feet electrically welded to the lower half. The roller bearings are the first application made by this company of such bearings to a large converter. The pedestal supporting the bearing is made entirely of plates, cut and bent to shape, and electric welded.

There were built during the year, four twelve-phase, 4200-kw., 270-volt converters which are probably the largest twelve-phase converters in service in this country or abroad. The transformers were split into two sections, half being mounted on either side and connected to the brush-holder studs by copper bars, thus making a compact installation.

Also there were built four 5800-kw., 580-volt, 25-cycle converters for electrolytic work, the largest 25-cycle converters yet made for such service.

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Induction Motors

The year 1927 resembled 1926 in the absence of spectacular or revolutionary achievements which specifically could be associated with the year in question. Satisfactory progress seems to depend more and more upon careful improvement of details in design, manufacture, and application. More complete and accurate knowledge of problems in lubrication, ventilation, balance and vibration, noise, and magnetic characteristics of materials, finally results in smaller, cheaper, and more satisfactory motors. Few really novel principles may be introduced into practical applications, but the principles already available are being more appropriately employed.

Quiet Motors

Increased use of motors within office buildings,

hotels, theaters, etc., has involved a demand for more rigorous standards of quiet operation. These standards are being met by more careful attention to several factors of design, especially of the magnetic circuit.

In addition to the improvements thus obtained in the reduction of magnetic noise, steps also have been taken with satisfactory results to reduce noise due to windage. In the case of some 2000-hp., 1800-rev. per min. blower motors for the Boston Edison Electric Light and Power Co., in which very quiet operation was desired, the result was secured by furnishing mufflers in the air outlet of the motors.

Totally Enclosed Motors

Lines of enclosed fan-cooled motors recently have been brought out which embody improved methods of circulating the air within the motor frame. These motors are much smaller and more economical than previous types, and so have extended the possibilities of applying motors in wet and dusty situations. The improvements in this type of motor represent a more exact knowledge of the process of removing and dissipating the unavoidable losses of the motors and the

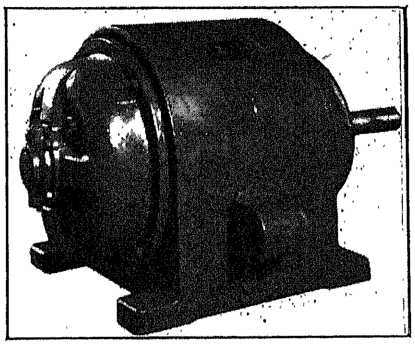

Fig. 33—Enclosed Ventilated Ball Bearing Induction Motor

reduction of these losses wherever possible. (Fig. 33.)

Low Starting Current Motors

The increasing demand for high-impedance motors with adequate starting and pull-out torque has been met by careful studies of the principles introduced many years ago by Boucherot and others. It is only in recent years that a successful compromise between the inherent limitations of this principle and the current requirements of industrial applications has been reached. In 1927 the field thus covered has been extended still further, and several manufacturers now offer extensive lines of motors of this type. One manufacturer has brought out a new motor having movable steel bars in the rotor slots, which give high reactance at starting, but which are thrown out by centrifugal force as the motor accelerates, thus securing lower reactance in normal operation.

Frequency Converters

Frequency changers of the synchronous-synchronous type have been covered under the synchronous machines.

There are two other types of frequency changers, both of which use induction motors.

The synchronous-induction type uses a synchronous motor in concatenation with an induction motor, and provides a voltage tie as well as a frequency tie between the two systems. Several of these sets have been in-

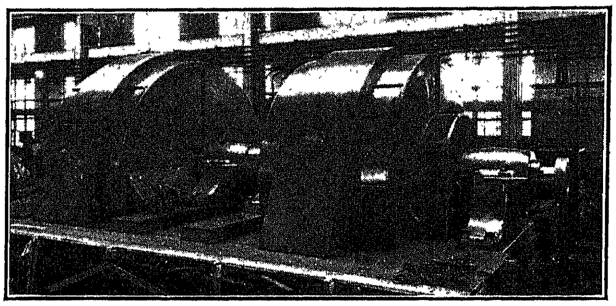

Fig. 34—15,000-Kw. Synchronous Induction Frequency Changer, 25/60 Cycles

stalled in Brooklyn and two more are in process of erection. The synchronous motor is 10 poles and the induction motor is 14 poles and rated 42,000 kv-a., 300 rev. per min., 13,800 volts stator and 2700 volts rotor. (See Fig. 35.)

Another of this type of 15,000 kv-a. has been installed by the Potomac Electric Light & Power Co.

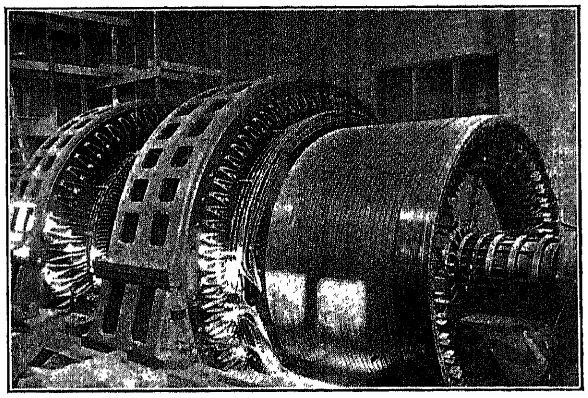

Fig. 35—35,000-Kw. Synchronous Induction Frequency Changer During Assembly as Seen from the Induction Motor End

Tests show 94.5 per cent efficiency at full load. (See Fig. 34.)

The adjustable ratio frequency changer uses an induction motor as the driving member and some means of speed control to adjust the speed to suit a change in frequency. Their advantages are that it is possible to use sets of smaller capacity than if they were of the synchronous-synchronous type. The amount of power and its direction can be controlled at the set by settings of the relays which control its action. It is much easier to synchronize due to the adjustable speed control on

the induction motor. These advantages are offset by increased cost, a little less efficiency, and added complications to the control.

In several cases, however, they have been chosen as the correct type, as at New Haven and Long Island R. R. in railway service and in several points on the Niagara Power 25-cycle lines where other 60-cycle systems desire power. The 25-cycle system is not so constant as desired by the 60-cycle systems and the adjustable ratio set allows the 25-cycle circuit to vary and still have constant 60 cycles on the synchronous machine.

Four of these sets, rated 5000 kw., were installed last year and are used to convert power from polyphase to single phase for railway service in the New York district. One of the sets for tying together power systems is now running at the Niagara Lockport & Ontario Power Co. These sets are the largest of this type, each consisting of a 25,000-kv-a., 2000-kw., 60-cycle synchronous machine and a 28,000-hp., 25-cycle induction motor, both at 12,000 volts. They tie in the 25- and 60-cycle systems and run at 300 rev. per min. The synchronous motors have 24 poles and the induction motors 10 poles. These sets deliver a constant 60 cycles on the synchronous machine when the 25-cycle

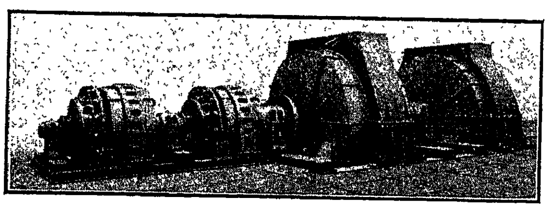

FIG. 36—SHOP VIEW OF 20,000-KW. ADJUSTABLE RATIO FREQUENCY CHANGER SET, 25/60 CYCLES

system varies between the limits of 2 per cent below and 1 per cent above normal. The auxiliary commutator machines are direct-connected to the main shaft, and are excited on their rotor winding through collector rings. (Fig. 36.)

HIGH-SPEED MOTORS

An increasing tendency to the use of high-speed motors for driving centrifugal pumps and air compressors was the practise in 1927. A relatively large proportion of these are being used for oil pipe line pumping, motors of as much as 250 hp. at 3600 rev. per min. being used for this purpose.

SHIP PROPULSION

Although synchronous motors have been found preferable in some types of ship-propulsion equipment, the cases in which induction motors are still required are more numerous than was anticipated at the time the synchronous motor drive was introduced.

During the year, the second electrically-equipped self-unloading ore-carrier for the Great Lakes was completed and put in service, after satisfactory trial trips. This vessel had induction type main propulsion motors, and is the largest and most powerful ore-carrier on the Great Lakes. Induction motor drive is required on account of the exacting standards of flexibility in maneuvering imposed by the conditions of operation. Toward the end of the year the two airplane carriers *U. S. S. Saratoga* and *U. S. S. Lexington* were placed in commission and have been operated on their own power, although not as yet to full capacity. These induction-motor equipments were designed several years ago, and during the protracted period of ship construction have attracted attention on account of the great concentration of power involved.

Each of the 8 motors in each ship is rated at 22,500 hp. at 320 rev. per min., providing 180,000 for the ship. The size of these induction motors in hp. rating has been exceeded only recently by the induction motor on the adjustable ratio frequency changer sets mentioned above.

STANDARDS

Agreements between the different manufacturers on standard shaft diameters and other dimensions have resulted in a recent general revision of general purpose induction motor designs. General advantage has been taken of this change to improve the design of bearings by the provision of larger oil wells and better methods of preventing oil leaks.

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D-C. MACHINES

The developments in d-c. machines have been in the increase of limits and reliability rather than in any startling discoveries. The commutation of extra large

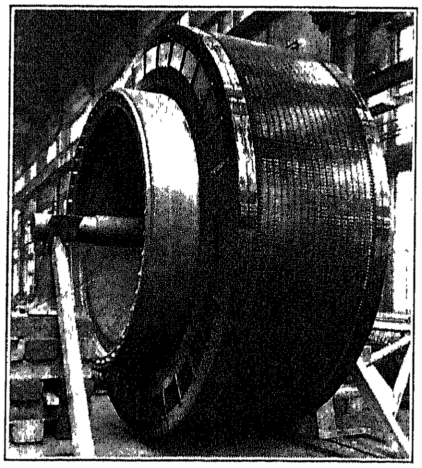

FIG. 37—ARMATURE FOR 7000-HP. REVERSING MOTOR SHOWING INVOLUTE EQUALIZER CONNECTIONS USED IN PLACE OF COMMUTATOR NECKS

currents has been accomplished; speeds have been increased; and the mechanical design has been simplified.

Commutation. To improve commutation and decrease losses, especially in large units, involute equalizer connections were placed between the commutator and the armature winding in place of straight commutator necks. Fig. 37 shows these equalizers on a 7000-hp. reversing mill motor.

It has also been found that wave windings are successful in larger ratings than can be built with lap windings. This wave winding insures equal distribution of current in the armature circuit without the use of equalizers by virtue of the unusual mechanical distribution of the winding. Eleven 13,000-ampere synchronous booster converters and two 14,000-ampere

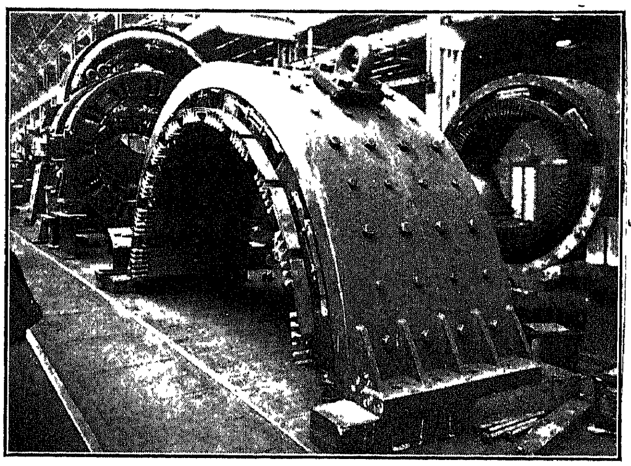

FIG. 38—A MAGNET FRAME MADE OF BENT SLABS WITH FLANGES FOR BOLTING HALVES TOGETHER WELDED ON

field-control converters have been built with this winding and have shown improved commutating performance and reduced losses from the absence of equalizer currents.

High-Speed Motors. Special requirements have led to the design of high-speed d-c. motors and results have been secured which would not have been thought possible even a few years ago. For example, during the last year, the Navy Department completed official tests on a special motor, the rating of which is 200 hp., 5000 rev. per min. This motor is used for driving a three-phase blower type compressor having a capacity of 3200 cu. ft. and a discharge pressure of 10 lb. New methods of design and construction had to be developed in order to build such a motor successfully. The peripheral speed of the armature is approximately 20,000 ft. per min. and the method of balancing was of the utmost importance. With the aid of a vibrometer, the rotor was balanced while rotating in its own bearings at the 5000 rev. per min. The bearings are flood-lubricated, oil being supplied by a separate motor-driven pump. The system of ventilation is simple and effective. The cooling air is actuated by the compressor and is drawn through the motor into the first phase of the compressor. The commutation was such that at the end of a 12-hr. duration test, the commutator surface did not show any sign of being burned or pitted.

Welded Construction. While welded frame motors have been on the market for a great many years, the use of this construction became much more general

during 1927. In many cases, such parts as magnet frames, bases, spiders, and brush rigging are now being fabricated. Fig. 38 shows a magnet frame made of bent slabs to which flanges for bolting the halves together and supporting feet are electrically welded. Armature spiders have been built up of plate and bar

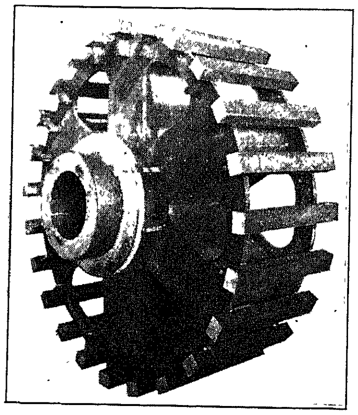

Fig. 39—Armature Spider Fabricated by Welding

material welded together on a steel hub for a large machine as shown in Fig. 39, and have been combined directly with the shaft for smaller machines, such as elevator motors shown in Fig. 40. The elevator motor shown in Fig. 40 is of further interest in that every part is of fabricated material without castings, except the

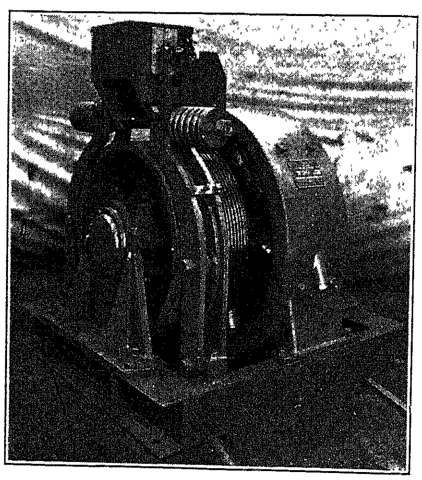

Fig. 40—Elevator Motor in Which Every Part is Welded Except the Rope Sheave

rope sheave. The base is representative of such built-up parts as a substitute for castings. During 1927, the use of welded bases for all motors, generators, and motor-generator sets was extended rapidly.

Adjustable-Speed Motors. The principal development in adjustable-speed motors is to extend the speed range secured by field control beyond the conventional four-to-one range. Ranges of five-to-one and six-to-one have been secured. To secure successful operation at these higher-speed ranges requires very careful design and very accurate test adjustments. These higher-speed ranges have been particularly valuable in connection with application to reversing planers.

Marine. Motors for marine applications require special precautions against corrosion of the mechanical parts and against moisture in the windings. Although they must be installed in very cramped conditions, it is desirable to make major repairs without removing the motor from its position. If parts are not accessible, inspections will not be thorough. When failures occur, repairs must be made in the shortest possible time and often under extremely difficult conditions. Again, the application of motors aboard vessels may be taken as an example of the extreme length to which it is some times necessary to go in attaining accessibility. The case of propelling motors for submarines may be cited. The susceptibility of the lower field windings to failure has made it necessary to have some ready means of locating the defective coil and to arrange for its replacement without having to tear the ship apart. Test leads are brought out from the individual coils to a test terminal board and the whole magnet yoke is so arranged that it may be revolved in its housing and so make possible the repair or replacement of a defective field coil.

Standardization. For general purpose d-c. motors and generators, all manufacturing companies are now accepting such standardized dimensions as have been established by the National Electrical Manufacturers Association, with very considerable advantage, principally to the user, but also to the manufacturer. It is expected that during 1928 and 1929 still further progress will be made in this direction.

Outstanding Installations or Machines in Process of Manufacture

Marine. Keeping pace with recent developments, Diesel electric drive is used to power *old type* Shipping Board vessels which, with changes in the hulls, will enable them to have greater speed, greater economy, and increased cargo capacity. Each of these ships will use a double armature d-c. motor, direct-connected to the propellor and developing 4000 s. hp. at 2×750 volts. The motors have been designed so that the most efficient propellor design and speed can be used, which in this case is 60 rev. per min. These will be the largest marine motors of this type in the world.

Steel Mills. The heaviest powered tandem hot-strip mill in the country is driven by 6 d-c. motors, each rated 2500 hp., 160/320 rev. per min., 600 volts. Power is supplied from 3 three-unit M. G. sets, each rated 3000 kw.

The heaviest powered hot-strip mill in the country requires 21,811 hp. for the main roll drive, which includes both a-c. and d-c. motors. The three a-c. motors on the roughing stands are mechanically interchangeable, although their ratings and speeds are different. The three intermediate stands are driven by three 2000-hp., 300/500-rev. per min. d-c. motors.

The four finishing stands are driven by four 3000-hp., 180/360-rev. per min. d-c. motors. The main roll d-c. motors are supplied from three 4000-kw. three-unit synchronous M. G. sets. Auxiliary motors and excitation for main drives are supplied from separate M. G. sets.

For replacing a steam engine on a reversing mill in the Chicago district, a 6500-hp. d-c. single-unit 0/60/140-rev. per min. motor will be used. This is being installed on the opposite side of the mill to reduce the shut-down period of the mill during the changeover. Welded construction is used in the bedplate for this motor and also for the flywheel M. G. set which supplies power to it.

A novel feature in a rod mill drive is the use of synchronous motor drive for all the stands except the finishing stand, which is direct current. Power is obtained from an M. G. set which at the same time drives some of the stands. The five synchronous motors have a capacity of 9600 hp. and the d-c. motor is rated 1200 hp.

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Mercury Arc Rectifiers

At the close of 1927, there were in use in the United States and Canada 53 installations of mercury arc rectifiers having a total capacity of 44,450 kw., which may be compared with the 700,000 kw. installed in the entire world. As the first of the American rectifiers was purchased in 1923, fairly rapid progress in the adoption of the mercury arc rectifier for power conversion purposes is indicated. In the tabular appendix

TABLE I
MERCURY ARC RECTIFIERS IN RAILWAY INSTALLATIONS

	No. of sets	Tanks per set	A-c. Cycles	A-c. Volts	D-c. voltage	Kw. per set	Total kw.	Control
Calumet Gas and Electric Co. (Gary Street Railway)	1	1	60	33,000	600	500	500	Auto
Chicago, No. Shore & Milwaukee	1	2			600	1000	1000	Auto
Columbus Ry., Power & Light Co	1	2	60	13,200	600	1000	1000	Man.
Commonwealth Edison Co., Chicago								
Lawndale	1	2	60	12,000	620	1200	1200	Man.
Whipple	1	1	60	12,000	620	600	600	Man.
Laflin	1	2	60	12,000	1500	1500	1500	Man.
Front	1	2	60	12,000	1500	3000	3000	Man.
I. C. R. R. Co., Brookdale	1	2		12,000	1500	3000	3000	
Connecticut Company	5	1	25	13,900				
			60		600	1200	6000	Man.
	2	1	25					
			60	13,900	600	1200	2400	Auto
Delaware, Lackawanna & Western R. R	1	1	60	4,150	600	200	200	Semi
Lethbridge (City of)	1	1	60	2,200	550	400	400	Man.
Long Island R. R	1	1	25	11,000	650	1000	1000	Semi
Long Island Hempstead	3		25		650	1000	3000	
Los Angeles Railway	2	1			600	500	1000	Auto
Milwaukee Elec. Ry. & Lt. Co	3	1	60	26,400	600	550	1650	Auto
Montreal Tramways	2	2	62½	12,600	600	1200	2400	
	1	2				1200	1200	
	1	2				2400	2400	Auto
Northern Indiana Pub. Serv. Co	1	2			1500	1500	1500	Auto
(Chicago, So. Shore & So. Bend Ry.)	3	1			1500	750	2250	Auto
North Shore Power	1	1	60	2,400	600	600	600	Man.
Philadelphia Rapid Transit	2	1			600	500	1000	Auto
Portland Elec. Power Co	1	2			1400	1500	1500	....
Pub. Service Co. of Northern Ill. (Illinois Central R. R. Co.)								
Volmer	1	2		33,000	1500	1500	1500	Man.
United Traction	1	1			600	500	500	Man.
Utilities Power & Light Co.								
(Dubuque Elec. Co.)	1	1	60	13,800	600	900	900	Man.
(Eastern N. J. Power Co.)	1	1	60	2,300	600	550	550	Man.
American Gas & Electric	1	1	60	13,800	575	300	300	Auto
City of Calgary	1	1	60	12,000	575	600	600	Semi Auto
Dominion Power & Trans. Co	1	1	$66^2/_3$	13,200	600	600	600	Auto
Canadian National Railways	1	1	60	4,160	600	1200	1200	Auto
Duquesne Light Co	1	2			600	1000	1000	Man.
Total	50						47,450	
LIGHTING AND POWER								
Ford Motor Company Power & Lt	1	2	50	13,200	250	550	550	Man.
Industrial	2	2	60	13,200	460	1000	2000	
New York Edison Company	1	2	25	11,000	260	570	570	....
Henry Morgan Department Store, Montreal	2	2			265	132	264	
Total	6						3,384	

to this report, details of these installations, including frequency, voltage, and character of service of these 53 installations are given.

Reference to this appendix shows that most of the rectifier installations in this country have been made on railway systems, the few rectifier installations for Edison systems and industrial use amounting to less than 3500 kw. or 7 per cent.

Of the railway terminal electrification voltage class (1500-volt), 12,750 kw. capacity or 25 per cent has been installed, the remainder of the railway installations being of the 600-volt class and amounting to approximately 68 per cent. No installation of rectifiers for main line electrification purposes has yet been made.

In a few railway installations, dependence has been placed entirely upon rectifiers; but in most instances, rectifiers have been reinforced by converters previously installed in the same or adjacent substation.

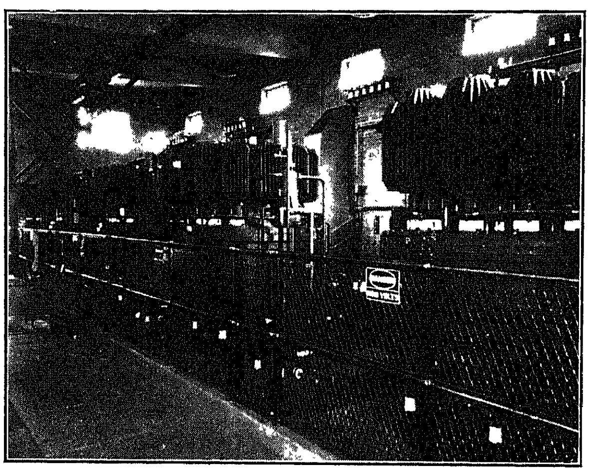

Fig. 41—Five 1200-Kw. Mercury Arc Rectifiers at Bridgeport, Conn.

The outstanding installation during 1927 was that of the Connecticut Company at Bridgeport, Conn., which includes five 1200-kw., 600-volt units, without other converting capacity. In another substation at Stratford, the same company installed two units of the same size with complete automatic control. Fig. 41 shows these five 1200-kw. rectifiers at Bridgeport.

Another large installation of three entirely automatically-controlled 1000-kw. 650-volt units was made in the Hempstead Station to supply the Long Island Railroad.

* * * * *

Operating experience of various companies indicates that rectifiers lend themselves generally to any of the usual methods of control, the 1927 trend toward automatic control having been noteworthy.

Parallel operation of rectifiers and converters has not introduced serious difficulties, although a satisfactory method of the control of regulating characteristics of the rectifier has not been introduced.

Although current capacities and efficiencies which would warrant the use of a rectifier on the three-wire Edison system have not yet been attained, the obvious advantages of the rectifier, including its adaptability to various voltages and frequencies and the hopeful laboratory development of the manufacturers, give promise of rectifiers suitable for this service.

Limitation of current capacity has been the greatest retardant to the further extended use of the mercury arc rectifier in this country. In the development of regulating devices it seems desirable that some method other than the transformer ratio adjustment or the use of the induction regulator should be preferred.

Continuity of service is adversely affected to the greatest extent by internal short circuits within the tank. It is also adversely affected by impaired insulation within the tank and by the liberation of gas from the anode. Service restoration following interruptions which do not involve impairment of the vacuum is a simpler procedure than with synchronous apparatus, but when the vacuum is impaired the period of outages may be greater than with the flashover of a synchronous converter. Operating experience generally indicates the need of development of rectifiers along lines which will enable more rapid repairs when required within the tank. Elimination of the internal short circuit, which will dispose of this disadvantage, is hoped for, although it may be well to add that internal short circuits are usually not accompanied by impairment of the vacuum, and the rectifier may be put back into service immediately after an internal short circuit without any trouble.

Interference between rectifier and telephone circuits caused by the "ripple" in the rectified current depends largely upon the exposure between the circuits. Where the exposure cannot be reduced, band filters have been successfully used in the d-c. leads of the rectifier.

The advantages of the rectifier in voltages of 600 and above with respect to the converter for installation under limiting conditions of ventilation and permissible attendant noise are fully set forth in the manufacturers' statement which follows:

Manufacturers' Statement

Economic Advantages of Rectifiers over Synchronous Apparatus:

Greatly reduced foundation.
Fractional weight.
Decreased transportation difficulties.
Simpler erection.
Simpler operation.
Lower operating costs.
Noiseless and vibrationless operation.
Adaptability to automatic and remote control.
Absence of synchronizing requirements.
Instantaneous starting and stopping.
Easier replacement of parts.
Increase of efficiency with voltage.
Higher efficiency over whole load range.
Independence of frequency.
Adaptability to high or low d-c. voltages.
High momentary overload capacity.
Possibility of cooling entirely by circulating water.

Some troubles experienced in the past with rectifiers were caused by corrosions, backfires, failure of the automatic vacuum valve, and telephone interferences. Today we have the necessary means at hand to overcome all these troubles. The effect of corrosion can be reduced to a negligible value by using long rubber hose connections at the cooling water intake, and a yearly overhauling and painting of the rectifier water chambers, or by using a forced draft cooling system insulated entirely from ground. In the matter of telephone interference there may be cases which would be difficult to correct and might involve expenditures of considerable magnitude. Backfires have been practically prevented by special screens inserted in the arc stream. An improved automatic vacuum valve is available and is entirely reliable. Telephone interferences wherever experienced have been very successfully eliminated by installing a special filter equipment.

The mercury seal has proved exceptionally reliable and has made possible tanks of 8 to 10 ft. in diameter. Also there has been developed by one manufacturer a unique seal consisting of a fused joint between porcelain and metal. Bushings may be removed and replaced without injury to the seal. A comprehensive system of automatically operating auxiliaries, including evacuating equipment, has been developed and a scheme of transformer connections giving the maximum utilization of transforming material without the balance coil gives promise of successful service.

The auxiliary equipment of one make of rectifiers has been considerably simplified. Anode and tank heaters and M. G. set for ignition have been abandoned. The excitation and ignition transformer, the choke coil, and the various insulation transformers are all mounted now in a common transformer tank. The auxiliaries consist of the following parts only: low- and high-stage vacuum pump; excitation and ignition; relay and transformer.

European Developments. In Europe the rectifier is in a great measure responsible for the steady increase of the d-c. voltages on railway systems. Already 800, 1200, and even 1500 volts are commonly used on urban, suburban, and interurban lines, with a few at 2400 and 3000 volts.

A typical example of a main railroad electrification is the 1500-volt Amsterdam-Rotterdam line of the Dutch Railways, which receives all the power from 20 Brown Boveri rectifier sets. There are several large industrial plants in Europe which depend entirely upon rectifiers as their power supply.

The most remarkable rectifier installation at the present time is the one of the Berlin Rapid Transit Company. Its system is the largest one exclusively supplied by rectifiers with a substation located at almost every passenger station.

This secures the advantage of having the power converting equipment just where the load demand is maximum, and of reducing the d-c. transmission lines and losses to a minimum. Moreover, the stray currents are greatly diminished, and consequently their destructive effect is also reduced. The interferences between d-c. lines, telephone and signal lines due to the pulsation in the rectified current are therefore practically eliminated. Altogether, the feeding of the "city" and "outer circle" railway lines require 34 substations with a total of 98 rectifier units, amounting to a total of installed capacity of 117,600 kw. The suburban lines branching out from the urban and outer circle lines are fed by 9 substations, each equipped with three or four units. Their total aggregate capacity is 36,000 kw. The primary supply for all these rectifier substations is 30,000-volt, three-phase, 50-cycle. The d-c. voltage is 800 volts.

The initial substation equipment is being supplied by Brown Boveri for this system and comprises for the initial development:

92 Rectifier cylinders, rated for a continuous output of 1200 kw. at 800 volts, with vacuum pumps and auxiliaries.

90 Rectifier transformers O. I. S. C.

90 Absorption reactance coils.

136-2000-ampere high-speed circuit breakers.

Other complete units are being supplied by other companies as follows:

10—Siemens Schuckert Works

10—Allgemein Elect. Co.

10—Bergmann Co.

The decision of the German Railways Company to use mercury arc rectifiers exclusively for the electrification of the important Rapid Transit Railways system of Berlin is of utmost importance for the future development of this type of converting apparatus, and shows clearly the confidence the engineers have in this equipment. The electrification of the Berlin Rapid Transit system will be no doubt the largest and most up-to-date rectifier installation in the world.

Performance Standards. Owing to the comparatively recent introduction of the mercury arc rectifier into this country the formulation of performance standards has not been undertaken to date. Definite procedure towards this end is, however, now under way. Performance guarantees of European practise will be studied and steps taken to put the matter of performance standards on a logical basis without hampering development.

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Transmission and Distribution

ANNUAL REPORT OF THE COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

To the Board of Directors:

In addition to conducting its usual activities this committee has during the current year endeavored to establish a closer contact with those committees of other organizations whose interests lie in a large measure within the field with which it is concerned. It was felt that such cooperation would be mutually beneficial and would result in the presentation through the medium of the Institute publications of some material of general interest which would otherwise receive only limited circulation. It is believed that the present report has benefited very materially by this policy.

After considering some criticisms of the definitions contained in the "Wires and Cables" section of the A. I. E. E. Standards the committee deemed it advisable to have these definitions revised. A suggested revision has been prepared and placed in the hands of the Standards Committee.

The committee has been fortunate in securing several interesting and timely papers for presentation and publication by the Institute, some of which have not yet appeared. References to these papers will be noted under the appropriate headings in the following text.

OVERHEAD TRANSMISSION LINES

Lightning on Transmission Lines. The protection of overhead transmission lines from interruptions due to lightning flashovers remains a problem of outstanding importance and in order to make more quickly available records of operating data on the protective value of ground wires, fused grading shields, and wood or combination steel and wood transmission line structures with regard to reducing lightning flashovers, a subcommittee undertook to collect as much information in this field as possible. A certain amount of information has been obtained and is presented herein, but more complete data are being sought and it is hoped to be able to present at an early date the inferences to be derived therefrom.

Table I gives data submitted by seven companies. Since no means avail to make direct comparisons of thunderstorm severity, it is obvious that while inferences may be made, conclusions cannot be drawn from these data.

Better performance resulting from adding a ground wire to an all-wood line seems clearly indicated from the comparison of 1926 and 1927 experience with that of 1925 of the data reported by companies No. 1 and No. 5. Similar improvements in reliability are indicated when ground wires have been added to steel tower lines.

On the other hand the data on the wood pole lines without ground wires, reported by companies No. 5 and No. 6, indicate in general less outages than the data on steel lines with ground wire, reported by others, indicating the apparent value of the wood as insulation in reducing flashovers.

Western companies report bird troubles as being more severe than those due to lightning, and wood construction very advantageous in this respect as shown by the data submitted by Company No. 6. However, there seems to be a crystallization of sentiment in the West in favor of steel towers with suitable bird guards, because of the very considerable trouble experienced with destructive fires due to leakage currents with wood construction, especially at certain seasons of the year.

Further light on the protective value of the ground wire is indicated by a comparison of the relative flashovers between 13 lines without ground wires totaling 412 mi. and four lines with ground wires totaling 229 mi.

Both groups are associated with the same systems, the lines being located in four different Middle West states.

There were in 1925, 36 interruptions for lines without ground wires, as against 2.2 interruptions for lines with ground wires, per 100 mi. of circuit.

Records for twelve consecutive years on a 110-kv. double-circuit line some 140 mi. long with single ground wire show an average of less than four interruptions per year per 100 mi. from lightning, and such interruptions constituted but one-third of the outages from all causes in that period. This line is subjected to as many as 70 to 80 electrical storms each year.

It may be noted that Company No. 8 had 36 and 28 breaker openings per 100 mi. in 1926 and 1927 respectively, although a ground wire was in service. Although this number seems large there may be satisfactory explanations which would become apparent if the somewhat insufficient data were more complete.

For lower voltage lines, 22 to 66 kv., there is an increasing tendency to try to improve designs of wood

*POWER TRANSMISSION AND DISTRIBUTION:
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		R. J. C. Wood.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

28-103

TABLE I

Company No. 1	50 ft. wood poles & wood arms		
	1925	1926	1927
No. of storms	58	57	50
Breaker openings due thereto	56	20	28
Insulator replacements due thereto	25	8	7
Miles of circuit—66 kv	71.2	71.2	71.2
Breaker openings per 100 mi	78.8	28.1	39.4
Insulator replacements—per 100 mi	35.2	11.25	9.85
Ground wire	No	Yes	Yes

Company No. 1	Steel tower lines		
	1925	1926	1927
No. of storms	57	50	50
Breaker openings due thereto	7	6	3
Insulator replacements due thereto	9	10	1
Miles of circuit—66 kv	96	48	48
Breaker openings per 100 mi	7.3	12.5	6.25
Insulator replacements—per 100 mi	9.4	20.8	2.08
Ground wire	Yes	Yes	Yes
Fused grading shields	No	No	Yes

Company No. 4	Steel tower lines		
	1925	1926	1927
No. of storms	65	67	70
Breaker openings due thereto	32	27	37
Insulator replacements due thereto	45	10	115
Miles of circuit—132 kv	140	372	401
Breaker openings per 100 mi	23	7.25	9.25
Insulator replacements—per 100 mi	32.3	2.70	28.7
Ground wire	No	Yes, partially	Yes

In 1926, 50 mi. were unprotected all year, and 256 mi. were unprotected by ground wire until after June 1st; fourteen storms were recorded prior to June 1st.

In 1927, 50 mi. were still unprotected by ground wire until after October 1st; sixty-four storms were recorded prior to October 1st.

Company No. 5	Wood pole lines		
	1925	1926	1927
No. of storms	2	2	3
Breaker openings due thereto	0	0	0
Insulator replacements due thereto	0	0	0
Miles of circuit—110 kv	29.1	29.1	29.1
Ground wire	Yes	Yes	Yes
Average height of ground wire	48 ft.	48 ft.	48 ft.

Company No. 5	Wood pole lines		
	1925	1926	1927
Number of storms		5	12
Breaker openings due thereto		1	3
Insulator replacements due thereto		0	3
Miles of line—110 kv	0	120	237
Breaker openings per 100 mi		.83	1.27
Insulator replacements per 100 mi		0	1.27
Ground wire		No	No

Company No. 5	Wood pole lines		
	1925	1926	1927
Number of storms	5	7	18
Breaker openings due thereto	0	3	7
Insulator replacements due thereto	0	3	3
Miles of circuit—55 kv	614	494	672
Breaker openings per 100 mi	0	.61	1.04
Insulator replacements—per 100 mi	0	.61	.45
Ground wire	No	No	No

Company No. 6	Wood line 1927	Steel line 1927
Miles of line—110 kv	41.7	42.8
Flashover from lightning	1	4
Flashover from birds	0	11
Flashover from insulator failure	0	1
Ground wire	No	No

These lines are installed between the same substations.

Company No. 8	Steel tower line		
	1925	1926	1927
Number of storms	No record available		
Breaker openings	1	9	7
Miles of circuit—154 kv	25	25	25
Breaker openings per 100 mi	4	36	28
Ground wire	Yes	Yes	Yes
Height top line conductor	65 ft.	65 ft.	65 ft.

Company No. 9	Steel tower line		
	1925	1926	1927
Number of storms	No record available		
Breaker openings	1	1	0
Miles of circuit—110 kv	104	104	104
Breaker openings per 100 mi	0.96	0.96	0
Ground wire	Yes	Yes	Yes
Height top line conductor	65 ft.	65 ft.	65 ft.

Company No. 12	Steel tower line		
	1925	1926	1927
Number of storms	37	39	31
Breaker openings due thereto	19	34	8
Insulator replacements due thereto	33	82	8
Miles of circuit—120 kv	41	81	120
Breaker openings per 100 mi	46.4	42	6.7
Insulator replacements per 100 mi	80.6	101	6.7
Ground wire	No	No	Yes

pole lines with a view to reducing lightning troubles by the use of wood pins, arms and braces, and by increasing the amount of insulation inserted in the guy wires.

Company No. 1 reporting on the value of fused grading shields shows a fifty per cent reduction in outages on two circuits, on one tower line, so equipped compared with two circuits on a parallel tower line protected by ground wire only. It also states that this type of protection functioned correctly two out of every three times, *i. e.*, cleared the follow-up dynamic arc before the breakers opened and thus avoided dumping the load. The record as to the performance of the individual fuses was even better—77 per cent correct operation, *i. e.*, 77 per cent cleared properly and were not the cause of a line interruption.

Another company desirous of trying out this type of protection on 132-kv. circuits reports that it has not as yet been able to find a fuse for that voltage which, after testing, it felt was safe to install for this purpose.

The subcommittee has also secured a contribution to the report covering some of the more theoretical phases of this subject, and this constitutes the following material having to do with the theory of lightning and ground wires being herein presented not particularly as representative of the views of the committee as a whole, but rather as being of general interest and stimulative of further thought and study on the more theoretical aspects of this subject.

Theory of Lightning and Ground Wires. The results of the work of a number of investigators during the past year have altered to some extent the conceptions regarding the nature of the lightning stroke and the manner in which it affects transmission lines. The fundamentals of the "breaking drop" theory of the accumulation of

the cloud charge, as proposed by G. C. Simpson, is generally accepted. According to this theory, the upward air currents in the front of the cloud, blowing past the condensed vapor in that region, break up the larger drops, as they form, and leave the divided parts with a positive charge. The passing air with finely divided spray carried off the corresponding negative charge to the upward and rearward portion of the cloud. Upon the recombination of the positive drops the potential is raised, due to the decrease in total surface; and likewise, in the negative part of the cloud the potential is raised as the charge is imparted to the vapor which condenses and forms into drops. According to this conception, the first part of the storm, and that with the heavy rain, is accompanied with the positively charged part of the cloud. The latter part of the storm, and the usually finer, drizzling rain, is accompanied with the negatively charged part of the cloud. Much of the accumulated charge of the cloud is carried to earth with the falling rain but the accumulation is, in general, more rapid than the dissipation by this means. The result is the familiar lightning flash between cloud and earth or between oppositely charged portions of cloud.

An electrical discharge between oppositely charged bodies starts, of course, when the stress at one of the electrodes reaches a state where ionization by collision begins. This state requires that potential gradient which gives free electrons a speed sufficient to knock off other electrons when they collide with neutral molecules. When an electron with this speed collides with a molecule but does not succeed in knocking off another electron, a considerable amount of heat is generated. If the stress reaches the breakdown potential of 30,000 volts per cm., the concentration of free electrons becomes so great, and the collisions with molecules become so frequent that the gas is heated to the point where thermal ionization begins. This forms the start of a streamer. Along such a streamer the gradient is low, which increases the stress at the ends. This further increases the concentration of ionization at the ends and promotes the progress of the streamer. Due to the difference between the speeds of negative electrons and positive ions, the speed of growth of the streamer toward the anode is much greater than that toward the cathode. This accounts for the difference between the growth of lightning strokes from negatively and positively charged clouds. However, in either case the speed is limited. It has been shown by various tests that with practical amounts of energy the maximum speed of growth of these streamers between electrodes of various shapes is of the order of one-tenth to one-fiftieth the speed of light. The completion of this arc establishes a conducting connection between the electrodes and an electrical current is free to pass, being governed by the impedance of the entire circuit involved.

In the discharge of a cloud to earth it is incorrect to consider the charge being released as concentrated in the first streamer. The streamer merely sets up the path, and as stated above, the growth is a relatively slow process. Considering the distances and speeds involved, it must take a time of at least 10 and probably 50 microseconds to accomplish this. After the path is established the charge is free to travel to earth as a traveling wave as fast as it can gather from the cloud. The progress of this is restricted, since the charge is distributed throughout a relatively non-conducting body. It is necessary for the path to branch out and collect the charge. Beyond this retarding effect, the rate at which the charge can pass to earth is determined by the potential of the cloud and the surge impedance of the lightning path. This surge impedance is a variable since it depends upon the diameter of the path and the

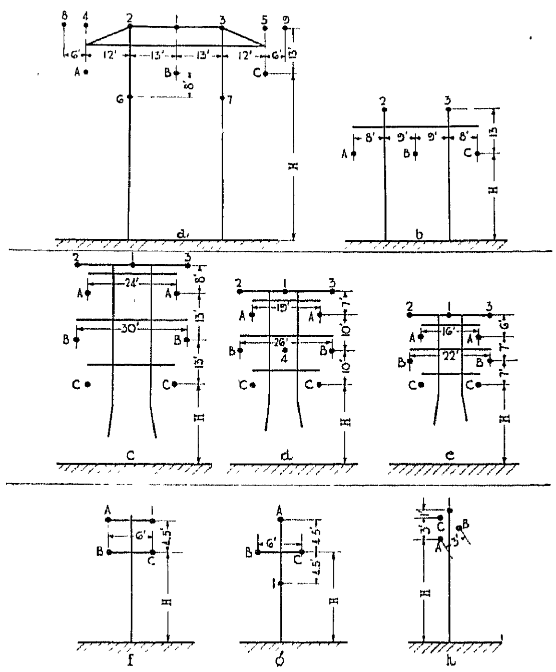

FIG. 1—TYPICAL ARRANGEMENT OF GROUND WIRES ON TRANSMISSION LINES

distance above the earth. Although it is not quantitatively known it definitely limits the intensity of the lightning flash. When the lightning strikes a transmission line directly, the traveling wave from the lightning path divides, and propagates in two directions, with two-thirds voltage, in the same manner as when an ordinary line branches into two parts.

It is easily seen that this phenomenon limits the intensity of the surge, and many of them are probably quite weak. There is considerable reason to believe that, of the lightning surges experienced on transmission lines, a larger percentage is due to direct strokes than has generally been believed. In order for an induced surge to attain important magnitude, not only must the gradient be very intense, but the discharge must be extremely rapid. The gradient falls off rapidly from

directly beneath the cloud outwards, and unless the discharge is extremely rapid the bound charge has time to distribute itself over the line.

It is now generally recognized that a great amount of protection is afforded by the use of ground wires on transmission lines. Much of the disrepute into which ground wires fell was due to poor mechanical installation and the use of non-weather-resisting material, which did not provide a life comparable to that of the rest of the line. In the installation of ground wires the same degree of weather resistance and the same quality of installation should be used as in the rest of the line so that the ground wires do not fail previous to the line conductors.

Ground wires are valuable in protecting the line both from induced and direct strokes. The manner in which the ground wire protects against induced strokes is as follows: Due to the slow rate at which the cloud electrostatic field is established, all conductors, both ground wires and line conductors, may be considered grounded. Therefore, a charge passes up on the conductors of such a value that the potential of the cloud field is exactly neutralized at the positions of the conductors, and the conductors remain at ground potential. The potential on a body is determined not only by its own charge but by the charges on all other bodies in the vicinity. Therefore, in the presence of the ground wire the charge necessary to keep the line conductor at ground potential is less than would be required were the ground wire not present.

The second effect of the ground wire takes place at the occurrence of the stroke. If all conductors were insulated the degree to which the charge would be bound would be similar on each, and the voltages would all rise in the same proportion. In such a case, the presence of more than one conductor offers no protection to each, since the charge on one conductor would raise the potentials on the others in the same proportion that it had reduced the bound charges. Furthermore, if the discharge of the cloud were instantaneous the ground wire would offer no protection, since the bound charges would then have no time to readjust themselves, and upon the disappearance of the cloud field the charges would be those which would raise the potentials of the conductors to the potentials of their positions in the cloud field before the stroke, but of opposite polarity. However, in the actual case the ground wire is grounded, and there is a certain time lag in the disappearance of the cloud field. It has been assumed that this time lag is sufficient to permit the necessary readjustment of charges on the ground wire to keep it at ground potential in the absence of the cloud field and the presence of the charge on the line conductor, the latter not being able to get away on account of the higher insulation and the rapidity of the field collapse. During the past season, klydonographs have been connected to ground wires at a number of locations, and the highest potentials recorded near a tower were of the order of 20,000 volts, which verifies the validity of the above assumption. It is obvious that, in order to remain at ground potential in the presence of the charge on the line conductor, the new charge on the ground wire must be of opposite polarity. This charge of opposite sign reduces, rather than raises, the potential on the line conductor due to its own charge. A simple way of stating the effect of ground wires in connection with induced strokes is, that it decreases the capacity of the line conductor to ground before the stroke and increases this capacity after the stroke.

Quantitatively, ground wires reduce the potentials induced on lines by lightning by from 25 to 75 per cent, depending upon the number and arrangement of the ground wires. The number of ground wires to use is of course an economic problem to be considered in relation to the amount of protection desired.

The most efficient arrangement of the ground wires is that which gives the greatest geometrical mean radius of the ground wire system and the least geometrical mean distance of this system from the conductors being protected. Table II gives the protection afforded by various numbers of ground wires on lines of various standard voltages.

The amount of protection afforded by ground wires against direct strokes is not so easily determined. However, since the ground wires are, or should be, located above the line conductors they are much more likely to receive the stroke of lightning than the conductors themselves. In view of the limitation of the intensity of the lightning stroke, as discussed above, it is easily seen that the less severe strokes might hit the ground wire and still not induce sufficient voltage on the line conductor to cause a flashover.

The protection against flashover afforded by the use of ground wires is much greater than the percentage reduction in voltages. If the number of lightning surges of any given potential is plotted against the voltages, the resulting curve resembles a rectangular hyperbola. From this it is seen that of those lightning strokes, both direct and induced, which cause flashover, those that are not more than twice the flashover voltage of the insulators are much more numerous than those which are many times that value. Therefore, if each surge is reduced to one-half its voltage, the number of flashovers is reduced by a much larger factor. Operating experience of the past few years seems to indicate that on the higher voltage lines flashovers are practically eliminated by ground wires which give a 50 per cent reduction.

Topography in Relation to Lightning Flashovers. An investigation of the flashovers which have occurred on the Cahokia–Crystal City transmission line, which was put in service May 11, 1925, indicated a close relationship between the topography of the surrounding territory and the flashovers on the line. This relationship was demonstrated by plotting on a topographical map the location of all the flashovers whose positions

TABLE II

THEORETICAL PROTECTIVE VALUE OF GROUND WIRES

Line			Ground wires			Per cent reduction				Induced crest voltage for a gradient of 50 kv. per ft.		
Kv.	Fig. I	H*	No.	Location	Dia. in.	A	B	C	Ave.	A	B	C
220	a	50	0							2500	2500	2500
	a	50	1	1	1/2	21	31	21	24	1980	1720	1980
	a	50	2	2, 3	1/2	36	45	36	39	1600	1370	1600
	a	50	3	1, 4, 5	1/2	48	55	48	50	1300	1120	1300
	a	50	4	2, 3, 6, 7	1/2	48	61	48	52	1300	975	1300
	a	50	5	1, 4, 5, 6, 7	1/2	55	66	55	58	1120	850	1120
220	b	27	0							1350	1350	1350
	b	27	2	2, 3	1/2	34	44	34	37	890	760	890
132	c	45	0							3550	2900	2250
	c	45	1	1	1/2	29	26	24	26	2530	2160	1700
	c	45	2	2, 3	1/2	45	39	37	40	1930	1760	1410
	c	45	2	4, 5	1/2	48	41	39	42	1850	1700	1370
	c	45	3	2, 3, 6	1/2	51	52	51	51	1760	1410	1110
110	d	40	0							3000	2500	2000
	d	40	1	1	1/2	30	26	25	27	2090	1850	1490
	d	40	2	2, 3	1/2	48	42	40	43	1560	1440	1190
	d	40	3	1, 2, 3	1/2	59	51	49	53	1230	1220	1020
66	e	35	0							2450	2100	1750
	e	35	1	1	1/2	31	28	26	28	1690	1510	1290
	e	35	2	2, 3	1/2	49	43	42	45	1250	1200	1010
	e	35	3	1, 2, 3	1/2	60	54	51	55	980	970	830
	f	26	0							1525	1300	1300
	f	26	1	1	3/8	28	29	36	31	1095	930	835
	g	26	0							1525	1300	1300
	g	26	1	1	3/8	15	22	22	19	1300	1020	1020
33	h	30								1500	1575	1650
	h	30	1	1	3/8	38	40	46	42	930	945	890

H* = Height of lowest conductor.

have been reported since the line was put in service.

This line follows the low lands on the Illinois side of the Mississippi River to a point opposite Crystal City where it crosses to the high bluffs on the Missouri side. On the western side there are no high hills, except those near Crystal City. On the eastern side, steep bluffs parallel the line almost for its full length at a distance of from one to three miles. The prevailing path of the storms in this part of the country is from the directions between southwest and northwest.

The flashovers have occurred in groups with four to five miles having excessive flashovers and adjacent sections of similar length having but few. At the southern end, clouds pass over the high hills on the west side of the river and discharge to or near the line, causing a large number of flashovers. Farther north the clouds coming from the southwest do not pass over any high hills, retain their charge, pass over the bottom lands and discharge to the bluffs on the eastern side. At the time of discharge the cloud probably extends back over the line and the sudden release of the charge induced on the line by the passage of the cloud over it causes flashover. The nearer the line to the bluffs the greater the number of flashovers.

A number of flashovers along two miles of line, some three or four miles south of Cahokia, cannot, however, be accounted for on the above basis.

From this study, it appears that short sections of ground wire placed over the portions of the line most subject to flashovers should be almost as effective from the standpoint of protection as a ground wire over the entire length. Eight miles of ground wire divided into four sections would include those parts of the line upon which 70 per cent of the flashovers have occurred. The line is a double circuit one, 31 mi. in length. Two miles of ground wire have been installed over the Missouri bluffs and the other six miles will be installed as outlined above. It may well be that partial protection of this type will offer a maximum of insurance for a minimum of investment.

Symposium on Surge Voltage Investigations. Attention is called to the symposium on surge voltage investigations which is on the program of this convention and is being presented under the auspices of this committee (see p. 1111). Some of the papers in this group are in the nature of reports of progress of investigations which are not as yet completed and further reports will be awaited with the same interest with which the present papers will undoubtedly be received.

One paper of this symposium, entitled *Surge Voltage Investigation on the 132-Kv. Transmission Lines of the American Gas & Electric Co.*, presents the preliminary results of an extensive klydonograph layout which was planned and placed in operation during 1927 in connection with studies of the Subcommittee on Lightning. The investigation was made possible through the co-

operation of the General Electric Co., the Westinghouse Electric & Manufacturing Co., and the American Gas & Electric Co.

The data secured during 1927 require further study and are too incomplete at present for many definite and final conclusions to be drawn. Switching surges were recorded up to 5.2 times normal to ground, checking quite closely previous data on this phase of the problem: All switching surges were either highly damped or unidirectional with small magnitude. These surges do not appear to be at all troublesome to line or apparatus, at least in the line investigated. Lightning voltage surges were recorded up to 4.8 times normal and in one case where the line tripped over 19 times normal was found. Of the surges recorded 57 per cent were positive, 18 per cent were negative, and 25 per cent oscillatory.

Lightning arrester discharges were found as high as 2620 amperes in the neutral leg of a four leg oxide film arrester on a 132-kv. system. Another case of 1260 amperes was observed. Both currents were negative initially, the latter being highly damped.

Voltages on the protective ground wire were observed as high as 20,000 volts in one case, and many voltages were recorded in the order of 2000 to 3000 volts.

The work, so far, indicates that surges of lightning origin having an initially high value, do not spread far on the line before rapid attenuation reduces them very materially. The waves are highly attenuated in the first five miles or so of travel.

Voltage surges due to switching were found to travel the entire length of the 73-mi. line with little apparent attenuation. There was a noticeable reflection of the voltage at the open end of the line which died out in a few miles of return travel.

On these particular lines it was found that the voltage surge on deenergizing the line was about double that which was found on energizing the line. Switching on these lines was done on the 132-kv. circuit, and not on the low side of the step-up transformers, a condition which is thought to have influenced the results. Further data are being obtained on this feature of line switching.

The field investigation is being continued in 1928 and it is expected that after the data for 1928 have been collected and assimilated a fairly complete report can be presented.

Insulation of Transmission Lines and Connected Apparatus. The tendency in power transmission has been to increase the insulation of some portions of the system, particularly the line, to a point at which it is fairly immune from flashover due to lightning. This tends to place a greater stress on the other apparatus and therefore requires a corresponding increase in its insulation.

The papers on *Relation between Transmission Line and Transformer Insulation,* by W. W. Lewis, (see p. 1111) and *Rationalization of Transmission-System Insulation Strength,* by Philip Sporn, (see p. 1132) which were presented at the New Haven Regional Meeting, point out the anomalous features of this situation and suggest concrete steps to be taken toward its rectification.

Horizontal Spacing of Transmission Line Conductors. While the horizontal spacing of conductors in a transmission line is ordinarily determined by the clearance necessary at the tower to permit the swinging inward of the insulator strings, there are, nevertheless, cases where this spacing is determined to avoid danger of contact of the conductors out in the span. Among such cases are the occasional lines with six horizontally spaced conductors on one tower (as in the case of the Davis Bridge Line of the New England Power Company) and long spans; also some wood pole lines where the poles do not carry a ground wire.

A paper by Mr. P. H. Thomas (see p. 1323), covering this subject in detail and proposing an empirical formula for the determination of the necessary spacing as depending upon the danger of contact out in the span, has been secured and is being presented at this convention.

Transmission Line Conductor Vibration. Investigations have been carried on through the year on the vibration of transmission line conductors of various materials in service. These records obtained in the field have been supplemented by experimental work at the Carnegie Institute of Technology in Pittsburgh.

The general results of these records and investigations are covered in a paper by Theodore Varney, (A. I. E. E. Quarterly TRANS., 1928, Part 3, p. 799), read at the St. Louis Regional Convention on March 9, 1928.

These investigations confirm the fact that resonant vibrations are due to wind of rather low velocity. The effects of these vibrations are more marked when the conductor or cable consists of a strong material giving a high elastic limit, as would be expected.

It appears that practically all wires or stranded cables suspended in the air are in a constant state of vibration. It is only, however, when the wind velocity is uniform throughout the span and bears certain definite relations to the elastic characteristics of the span that resonant vibration of considerable amplitude is set up.

Resonant vibration of considerable amplitude has been observed and recorded in many cases. In comparatively few of these cases has damage to the conductor or cable resulted. It is to safeguard such cases, however, that the investigation has been carried on and comparatively simple methods for overcoming these difficulties have now been suggested.

In view of the complexity of the problem and the consequent difficulty of prophesying in advance whether or not trouble may arise, it appears probable that some one of the several comparatively simple safeguards which have been developed should be considered in the design of any new transmission line of importance.

It is believed to be a simple and sound principle to reinforce a transmission conductor at its point of support,

particularly if the spans are long, the weather conditions severe, and the line important.

Movements of Overhead Line Conductors during Short Circuits. A paper by W. S. Peterson and H. J. McCracken, Jr., covering a considerable amount of experimental data on the movements of overhead line conductors due to electromagnetic forces under short circuit conditions was presented at the Pacific Coast Convention in August (A. I. E. E. Quarterly TRANS., Vol. 48, No. 1, Jan. 1929). In overhead lines where heavy short circuit currents are encountered, this is a feature of design which cannot be neglected, and it is hoped that the paper mentioned, together with other available information, will make possible a more rational treatment of this problem.

UNDERGROUND CABLES

General Review. The outstanding feature of underground transmission during the year is the placing in service in the summer of 1927 of 18 mi. of 132-kv. lines in Chicago and New York. These installations were described before the Institute at the Chicago Regional Meeting in November 1927. There have been no electrical failures on these installations, and the only troubles have been minor oil leaks in joints and other appurtenances and a few leaks in cable sheaths. In all cases of leaks the repair work was deferred until the line could be taken out of service without inconvenience to the operating company.

No marked developments in the design of underground cable for general use have taken place during the year. Impregnated paper insulation is very generally employed and wood pulp paper is rapidly replacing manila paper. The advantages due to the superiority of the mechanical properties of manila rope paper over wood pulp paper have very largely been overcome by reason of improvements in the production methods with wood pulp paper. On the other hand, the latter has a higher dielectric strength than the manila paper which has thus far been used and research investigations have shown it to have as high temperature limitations. Sector shape conductors are being very largely used in high voltage three-conductor cable. Shielded type three-conductor cable is being marketed by a number of manufacturers for the higher operating voltages and some manufacturers of single-conductor cable for extra high voltage three-phase operation are recommending the use of the shielded type of construction for such cable.

All of the available evidence indicates that on the whole there has been a distinct improvement in the quality of high voltage cable during the past few years. Statistics on more than 5,000,000 ft. of such cable purchased under rigid specifications by a group of central station companies show that only 3.22 per cent of the cable submitted during 1927 was below the standards prescribed by the specifications,—the lowest of continually decreasing percentages during the past five years. There has been a steady increase in dielectric strength of cable during the past few years. Dielectric losses and power factor are at about a minimum,—the average power factor for cable with a wide range of voltage ratings and sizes being about 0.6 per cent at room temperature and operating voltage.

Another outstanding feature has been the marked decrease in the effect of bending on the dielectric strength of paper-insulated lead-covered cables. For the past two or more years cable could be subjected to a very severe bending manipulation without any appreciable effect on the dielectric strength.

Existing specifications provide certain maximum allowable operating temperatures for impregnated-paper-insulated cables depending upon the rated voltages. Neither these specifications nor the standards of the A. I. E. E. specify a method of determining the maximum temperature in the cable during operation. In order to make a start on clearing up this situation the subcommittee on impregnated-paper-insulated cable research has made arrangements with the Massachusetts Institute of Technology for studies on the thermal resistivity of impregnated paper insulation, including the devising of a standard method of measuring the resistivity which will be acceptable to the manufacturers and users.

Cooperative Activities. A number of the central station companies that purchase large quantities of underground cable annually, cooperate in the inspection and testing of new cable, in the analysis of a large amount of inspection and test data thus made available, and in a certain amount of experimental research work. These statistical analyses are the basis of the above statements in reference to quality improvement.

Among the research studies which have been made, one on the relative dielectric strength of single-conductor versus three-conductor cable indicated that single-conductor cable has a dielectric strength which, if expressed as the average voltage gradient which will cause failure in 10 hr., is about 60 per cent greater than that of three-conductor belted type cable, the advantage over shielded three-conductor cable being about half that amount.

Manufacturers of cable, however, are in good agreement that the advantage in dielectric strength of single-conductor cable as compared to three-conductor belted cable for these conditions is only about 30 per cent, with a corresponding reduction to possibly 15 per cent for shielded three-conductor cable. Further investigation of the data will probably serve to reconcile the discrepancies between these figures.

Another rather extensive investigation has established the relationship between life and voltage for modern cable, namely, that the life varies inversely with approximately the sixth power of the voltage in the case of single-conductor cable and approximately the seventh power of the voltage in the case of three-conductor cable within the range of the test.

Effectiveness of Specifications and Cable Performance.

The effectiveness of specifications and the accompanying inspection and tests in guaranteeing satisfactory service of cable are often questioned and few data exist from which definite conclusions may be drawn. Obviously the answer to this question can be found only by following the history of inspected cable after it goes into service. The importance of this question and the still greater importance to the operating engineer of thoroughly reliable records of cable performance have been recognized and all of the important data in connection with all failures of cable in service on a number of the larger systems are now being systematically collected. It is believed that these studies will yield some very important results but they have not yet been continued long enough to justify conclusions. However, it has already been found that a very considerable percentage of the sections of cable which failed in service without external cause had some abnormal feature of more or less significance in the original inspection record.

Quality Rating. It is generally recognized that all items of inspection and test are not of equal value, and that no one characteristic determines the quality of a given piece of cable. On the other hand it is probably true that no two engineers will agree as to just which characteristics do determine cable quality. Nevertheless it is appreciated that a method of weighing characteristics, assigning grades on a scale of test performance for each characteristic and thereby obtaining a single figure of merit for a given lot of cable, would furnish an engineer with a useful means of evaluating that cable. Such a procedure of quality-rating has been set up and is now being applied in the cooperative work referred to above. Such a procedure, even though strictly empirical, will, if it proves to coordinate with service records, be of great value to the industry.

Losses in Armored Single-Conductor Cables. The calculation of potential drop and energy loss in single-conductor steel armored cables used for three-phase circuits is not susceptible of accurate predetermination with the information now available.

In 1909, J. B. Whitehead and H. W. Fisher (TRANS. A. I. E. E., Vol. 28, p. 737, and TRANS. A. I. E. E., Vol. 28, p. 747 respectively) published some experimental data on this subject supplemented by theoretical discussions. The Whitehead formulas are revised in the light of further discussions in Wm. A. Del Mar's *Electric Cables*, 1924, p. 142.

Since that date the subject of drop in *unarmored* single-conductor cables has been very fully discussed in series of monographs in the *Journal* of the Institution of Electrical Engineers (London 1926 and 1927) and the theoretical principles evoked seemed to warrant the more careful study of the case of armored cables.

The main features that differentiate the latter from the former case are the difficulty of calculating the magnetic flux in the steel wires in view of the indefiniteness and variability of the air-gaps between them and the variability of the magnetic properties of armor wire.

The variety of iron armored single-conductor cables tested and the data obtained have not been sufficient to permit establishing a generally applicable calculating procedure for circulating currents and losses. While the data available cover sufficiently well for practical use the loss calculations for the few designs considered, iron armored cables of radically different design would probably require additional empirical data to be derived from tests, as a basis for the calculations. If the proper additional tests were made for a few other types of armor designs, a more general calculating procedure could probably be established.

A paper[1] is under preparation reviewing the knowledge at hand, and reporting the results of recent tests and analysis as a further step of progress toward a more general understanding of the problem.

In general the use of copper armor in place of steel will greatly reduce the losses in a submarine cable. In many cases either copper or iron armor is mechanically feasible; and the question as to which should be used in a given project will then be decided on an economic basis. The paper will include an analysis of the economic factors involved.

Alternating-Current Electrolysis of Lead Cable Sheaths. The use of single-conductor cables in separate ducts for three-phase circuits of high voltage has led to the adoption of various methods for the reduction of induced currents in the sheaths. These schemes entail a-c. potentials from the sheaths to ground of varying magnitudes and the question of whether electrolytic corrosion of the cable sheaths is likely to result from this practise is of considerable importance.

The phenomena involved in the alternating current electrolysis of lead are complicated by the chemical nature of the electrolyte. However, B. McCullum and G. H. Ahlborn state that in general under ordinary soil conditions electrolytic corrosion appears to be practically negligible when the period of the cycle is not greater than about five min. For the details of their findings reference should be made to Tech. Paper 72, Bureau of Standards 1916.

J. L. R. Hayden (TRANS. A. I. E. E., Vol. XXVI, p. 201) comes to the conclusion that electrolysis on alternating current rarely exceeds one-half of one per cent of the electrolytic action of the corresponding direct current.

Hayden also found that the superposition on an alternating current of 1.5 per cent of its value in direct current protected the lead against corrosion, the effect of course occurring when the cable was negative to the ground. E. R. Shepard (TRANS. *Am. Electro Chem. Soc.* 31, 239-51, 1921) in a paper entitled "Electrolytic Corrosion of Lead by Continuous and Periodic Currents," finds that with direct current the coefficient of corrosion in both tap water and earth decreases with an increase

1. By O. R. Schurig, H. P. Kuehni, and F. H. Buller.

in current density, reaching a minimum of about 50 per cent for current densities of five milliamperes per sq. cm. The theoretical maximum of 100 per cent is found for low current densities of the order of 0.5 milliamperes per sq. cm. and less.

If, however, certain salts are present in the electrolyte so that the lead ions may react to produce an insoluble compound a comparatively large amount of corrosion may occur even with alternating current. Further investigations of this subject are under way and will doubtless add much valuable information to our present supply, which is none too complete.

It may also be appropriate to mention here that some trouble has been experienced with lead sheath corrosion due to the formation of a red lead oxide. The 1915 report of the N. E. L. A. Committee on Underground Construction indicated that reversals in polarity of the sheath of long duration would be effective in producing corrosion of this type. More recent results indicate that such corrosion may occur quite independently of electrolytic action, but whether or not d-c. or a-c. electrolysis may be an important factor in accelerating such corrosion is somewhat in doubt. This subject was discussed at a special meeting during the April Regional Meeting, which was held in Baltimore, and as a result of investigations now under way more detailed knowledge will probably soon be available.

Summary. While, as stated, no startling progress has been made during the year, attention is called to the significance of the many cooperative activities now under way, a few of which have been mentioned above. The greater attention being given to underground cable by operating companies as evidenced by this cooperative work, and the constantly increasing research work being done by the operating companies individually and by the manufacturers, all justify expecting continued improvement in high-tension cable.

Papers Presented during Year. Several papers have been presented during the year which are of interest to engineers concerned with the design and operation of underground cables. Among them may be listed the following:

Joints in High Voltage Multiple Conductor Cable, by Thos. F. Peterson, TRANS. A. I. E. E., Vol. 46, 1927, p. 963.

The Influence of Residual Air and Moisture in Impregnated Paper Insulation, by J. B. Whitehead and F. Hamburger, Jr., JOURNAL A. I. E. E., Sept. 1927, p. 939.

High Voltage Measurements on Cables and Insulators, by C. L. Kasson, TRANS. A. I. E. E., Vol. 46, 1927, p. 635.

Electric Strengths of Solid and Liquid Dielectrics, by Wm. A. Del Mar, W. F. Davidson, and R. H. Marvin, TRANS. A. I. E. E., Vol. 46, 1927, p. 1049.

Influence of Internal Vacua and Ionization on the Life of Paper Insulated High Tension Cables, by Alexander Smouroff and Leo Mashkileison, A. I. E. E. Quarterly TRANS., July 1928, p. 731.

132,000-Volt Single Conductor Lead Covered Cable, by P. Torchio, L. Emanueli, W. S. Clark, A. H. Kehoe, C. H. Shaw, J. B. Noe, and D. W. Roper, A. I. E. E. QUARTERLY TRANS., Vol. 47, No. 1, January 1928, p. 186.

POWER LIMITS OF SYSTEMS

Further progress is reported in the development of methods for predetermining power limits of systems and of criteria for system stability. From this standpoint, important progress has also been made in synchronous machine theory.

A number of papers bearing on the problem of power transmission has been presented during the year. Three of these presented at the Winter Convention (bibliography references 1, 2, and 3) have added materially to the underlying theory as well as outlining methods for predetermining with practical accuracy those characteristics of synchronous machines which are of importance from the standpoint of stability. A paper on power limits with several machines connected to the system was presented at the Pacific Coast Convention (reference 4). A mechanical method of calculating power limits is described in a paper presented at Baltimore (reference 5).

Last year's report indicated the extent to which high speed or quick response excitation had been adopted as a means of preserving synchronism in a system during short circuits. The installations made to date are the Farmersville substation of the Southern California Edison Company, the Gatineau Falls Development of the International Paper Company, and the Conowingo Development of the Susquehanna Power Company. The experience obtained to date with these installations has been insufficient to draw any definite conclusions regarding their effectiveness in maintaining stability. Without such operating experience, the committee has no further statement to make except to repeat the opinion generally held, that there is a number of cases where quick response excitation may be advantageous. It is not a panacea for system troubles. The question of its application, of the quickness of response, and of the "ceiling" exciter voltage, should be determined by a study of the particular conditions of a given case. Certain limitations common to all systems, such as saturation effects and rotative speeds, have been covered in a recent article (reference 10). Although there may be cases where conditions would not warrant a special excitation system to obtain rapid voltage build-up, there are cases, nevertheless, which justify very special means to secure not only extraordinary quick response, but also a high value of exciter voltage. For illustration, such equipments have been purchased by the Philadelphia Electric Company as part of five 30,000-kv-a. condensers which are being installed at the Plymouth Meeting and the Westmoreland sub-

stations of Philadelphia Electric Company. No operating data, of course, are as yet available. Installations of this character have been described before the Institute and in the technical press (references 7 to 15, inclusive).

Further progress is reported in factory tests of power transmission, using voltage regulating devices, substantiating previous tests demonstrating the possibility of stable operation under a condition of dynamic or artificial stability, that is, at values of power considerably above the limit with fixed excitation (references 13 and 14). It is thus a promising development as regards increasing the maximum output of synchronous machines. It is expected that even if it is not necessary at the present time to transmit regularly values of power above the steady-state limit, there may be occasions when certain branches of a system may be momentarily loaded beyond the steady-state limit, due to switching operation, sudden load shifts, etc., and the devices referred to should prove beneficial under such conditions. Data have also been obtained indicating that these devices, in conjunction with exciters of appropriate characteristics, materially improve the transient stability of a transmission system, that is, the ability of a system to carry through short circuits, and that they assist in helping to steady down a system which has been set into violent oscillation as the result of a severe short circuit.

There is an urgent need for further field data. These data should take two forms:

a. Further tests on systems for which calculations have been made, as a check on such calculations.

b. Data secured during transients encountered in normal operation, by means of special recording devices, such as the automatic oscillograph and the high speed recorder. Preferably these data also should be obtained on systems for which calculations have been made.

Some work has already been done along the latter line, and has been reported to the Institute (reference 16). In addition, there is a need for further data on the total impedance in the path of short circuit currents flowing from conductor to neutral at the values of current ordinarily encountered in such short circuits. A method for obtaining these data, together with a discussion of the effect of ground resistance upon the stability problem, has recently been published (reference 17).

It is felt that in the problem of maintaining synchronism between all machines connected to a system during short circuits, very considerable benefit will be obtained by reducing as far as possible the magnitude and duration of the disturbance caused by a short circuit. It is not generally practicable to reduce the short circuit current by the introduction of series impedance in the path of load currents as this decreases the power limits directly. Since, however, most short circuits occur from line to neutral, considerable benefit may be expected from making use of means which limit the value of line to neutral short circuit current without increasing the impedance of the system to normal load current.

For illustration the following means are available:

1. In the case of an a-c. low voltage network by feeding the network from a number of small step-down stations, thereby limiting the current caused by a short circuit on the distribution system.

2. Grounding only part of the transformer banks at any one point.

3. The introduction of impedance devices in the neutral connection. Other means may be desirable in special cases.

In the belief that the trend in the future will be in the direction of reducing fault currents without increasing the impedance of the system to load currents, the committee therefore recommends that in the case of new systems or in the case of extensions to or changes in existing systems, consideration be given to means of reducing such fault currents.

For papers and articles reference should be made to the Bibliography (2) covering this subject.

ACKNOWLEDGMENT

The material in this report has been obtained from a multiplicity of sources and includes contributions made through the courtesy of committees of other organizations as well as those of subcommittees and individual members of this committee. Without making a detailed acknowledgment, the chairman wishes to take this opportunity of expressing to the contributors as a group the appreciation of this committee as well as his own personal thanks for the generous manner in which they have all given so unstintedly of their time and information.

PHILIP TORCHIO, *Chairman.*

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STABILITY LIMITS

4. *Static Stability Limits and the Intermediate Condenser Station*, by C. F. Wagner and R. D. Evans, TRANS. A. I. E. E., Vol. 47, No. 1, January 1928, p. 94.

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SYSTEM DATA

16. *Transients Due to Short Circuits*, by R. J. C. Wood, L. F. Hunt, and S. B. Griscom, TRANS. A. I. E. E., Vol. 47, January 1928, p. 68.

GROUND RESISTANCE

17. "Characteristics of Ground Faults on Three-Phase Systems," by S. B. Griscom, *Electric Journal*, April 1927, p. 151.

Discussion

D. W. Roper: Mention is made in the report of the underground 132-kv. cable installations in New York and Chicago. I think the report would properly be supplemented by a statement of the service record of that cable. There are approximately 36 mi. of cable in New York and 18 mi. of cable in Chicago. The latter installation has been in service nearly 13 months and the New York installation nearly 11 months. The total service record amounts to nearly the equivalent of 50 mi. of cable for one year and during this time there have been no electrical failures, a record which I believe is unequaled by any recent performance of any underground cable from the time when the first installation of a higher-voltage cable was installed in this or any other country.

The paper mentions also some trouble with red oxide of lead on underground cables in certain locations. There was a meeting at Baltimore to discuss the subject. The results of that meeting and subsequent experiments did not get reported to the Chairman in time to be included in this report and I thought they might be interesting.

The clue was given by a peculiar condition in Chicago, where a concrete conduit was cast in place. The conduit was so enclosed that air could not reach it readily. This conduit was connected to another conduit made of pre-cast sections and so located that water might drain from the first conduit into the pre-cast conduit. Corrosion was found on cables in both conduits, but mostly in the lower conduit.

In the disucussion at Baltimore it was brought out by cement experts that cement requires carbon dioxide for setting as well as moisture.

In the case of the monolithic conduit, there was abundant moisture, but apparently a deficiency of carbon dioxide. Evidently the carbon dioxide absorbed by the water seeping into the concrete structure from the surrounding earth was all given up to the outer portion of the concrete. The water, continuing its course through the concrete to the interior of the ducts, picked up the alkaline hydrates from the uncured concrete and then ran down through the conduit and into the other conduit. The alkaline hydrates attacked the lead sheaths principally in the pre-cured ducts, which are only slightly inclined. This was confirmed by analyses of the water taken from the ducts which show hydroxides of lead and calcium.

The action of these hydrates can be stopped temporarily by the application of carbon dioxide gas to the ducts or allow it to bubble up through the water in the ducts; but the relief obtained in this manner is only temporary. Analyses taken a few days after the application of the gas again show a dangerous amount of the alkaline hydroxides. The trouble has continued for over 15 months after the installation of the monlithic conduit, and a solution for the trouble has not yet been found.

In this case, where the corrosion was due to chemical action, the products of corrosion are generally from a yellow to a deep red color, while in mild cases of electrolysis extending over several years, the corrosion products range from a white to a light yellow in color.

The conclusion is that when ducts are cast in place at least a month should elapse to give the concrete time to set before cables are installed.

Harold Michener: I should like to say a little about vibration. We of the Southern California Edison Company think the subject of conductor vibration is very important and probably should be emphasized more than it is in this report. I think we have published more about our troubles due to conductor vibration than any other company. We feel that we have solved the problem, and that with the use of these vibration dampers we can hold any conductor so that it will not vibrate appreciably.

I think this should be considered very carefully in connection with the ground wires as well as in connection with the conductors. I would recommend particularly that those who are putting up ground wires in suspension clamps expecting them to prevent breaking of the ground wires at the points of support should keep very close watch of those points of support. We feel that when there is vibration the thing to do is to stop the vibration rather than try to put some arrangement at the points of contact that will ease off the deteriorating effect that the vibration has even though flexibility and easy entrance curvatures undoubtedly are of some benefit.

M. T. Crawford: Since submitting data to the committee from which the figures in Table I, Company 5, were compiled, I have secured additional data covering simultaneous years operation of another company's 110-kv. wood-pole transmission line running through the same territory. This line was built with a ground wire throughout, whereas the line shown in the committee report was without the ground wire. It is interesting to note that over a three-year period this line averaged 0.88 breaker openings per hundred miles per year, which is very close to the average of the values shown for the wood-pole lines without ground wires for Company 5 through the same period.

These lines are located in the Puget Sound region where lightning is comparatively infrequent, but with over a thousand miles of line and in a three-year period the results should be fairly indicative of the value of the ground wire and do not seem to show that the ground wire is economically justified under conditions obtained in this locality. As a result of this analysis, the Puget Sound Power & Light Company is now building additional 110-kv. wood-pole transmission lines about one hundred miles in length and no ground wire is being installed.

Philip Torchio: Numerous data have been collected in recent years regarding lightning disturbances on transmission lines and the preponderance of the evidence available indicates quite clearly that a great deal of protection may be expected from the use of ground wires. In some cases, such as the one mentioned by Mr. Crawford, the ground wire has not appeared to give the anticipated benefits and it is to be hoped that future records of operation and studies of the local conditions will disclose the reason for these variations. There are so many variables involved in studies of this kind that it is only by the analysis of records which cover a long period of time and which have been most carefully correlated with the local conditions that helpful deductions can be made. Fortunately, we now have the klydonograph which is of invaluable aid in carrying on these investigations.

Protective Devices

ANNUAL REPORT OF COMMITTEE ON PROTECTIVE DEVICES*

To the Board of Directors:

The principal work of the Committee this year has been—, *first,* arranging for and the actual preparation of papers for presentation at meetings of the Institute, of which there have been one or more presented at practically every meeting of the Institute, and *second,*—the work of standardization, the result of which work is reported below.

The work of the Committee has been carried on by subcommittees, each under the direction of its own chairman, and after the first organization meeting at New York in September further meetings have been held by the subcommittees individually. The subjects covered and the chairmen in charge of the subcommittees are as follows:

Current Limiting Reactors, A. H. Sweetnam, Edison Elec. Illum. Co., Boston, Mass.

Communication Circuit Protection, H. W. Drake, Western Union Tel. Co., New York, N. Y.

Industrial Control Equipment and Service Protection, R. C. Muir, General Electric Co., Schenectady, N. Y.

Lightning Arresters, J. A. Johnson, Niagara Falls Power Co., Niagara Falls, N. Y.

Circuit Breakers, Switches, and Fuses, J. M. Oliver, Georgia Power Co., Atlanta, Ga.

Reactors, W. H. Millan, Union Elec. Light & Power Co., St. Louis, Mo.

Subcommittee on Industrial Control Equipment and Service Protection

The subcommittee has prepared a revision of the A. I. E. E. Industrial Control Standards. This revision is in process and not finished sufficiently to be presented at this time.

Subcommittee on Communication Circuit Protection

The subcommittee has arranged for several papers and is giving active study to the question of standardization.

Reports of other subcommittees attached.

COMMITTEE ON PROTECTIVE DEVICES:

F. L. Hunt, Chairman,
H. R. Summerhayes, Vice-Chairman,
E. A. Hester, Secretary,

R. E. Argersinger, Raymond Bailey, A. C. Cummins, H. W. Drake, W. S. Edsall, L. E. Frost, James S. Hagan, Herman Halperin, F. C. Hanker, J. Allen Johnson, R. L. Kingsland, M. G. Lloyd, K. B. McEachron, W. H. Millan, R. C. Muir, J. M. Oliver, A. H. Schirmer, H. P. Sleeper, A. H. Sweetnam, F. D. Wyatt.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Proposed Standards for Lightning Arresters No. 28

Prepared by Subcommittee on Lightning Arresters

Corrected to April 12, 1928

Scope

The standards in this section shall apply to all types of lightning arresters embraced within the classifications given in paragraphs 28-100 and 28-101.

Service Conditions

28-1 *Usual Service Conditions.*—Apparatus conforming with these standards shall possess its specified characteristics and be capable of successful operation:

a. When and where the ambient temperature does not exceed 40 deg. cent. for air.

b. Where the altitude does not exceed 1000 meters (3300 ft.).*

28-2 *Unusual Service Conditions.*—The use of apparatus under conditions other than noted under (28-1) shall be considered as special. Other conditions which may require special consideration are:

a. Temporary overvoltage (such as may occur due to apparatus or line regulation, and/or generator over-speed, following sudden loss of load).

b. Sustained overvoltage (such as may result from accidental arcing grounds on one-phase of a circuit of which the neutral either is not earthed or is earthed through a considerable resistance).

c. Sustained overvoltage (such as may appear on non-earthed circuits by induction from unbalanced parallel higher voltage circuits in close proximity, or by contact with circuits of higher voltage).

d. Sustained overvoltage caused by removal of neutral connection to earth in combination with a grounded conductor (such as may occur on part of a system when it is disconnected from, or located at a great distance from, the part of the system having the neutral earthed).

e. Exposure to damaging fumes, vapors, or dusts.

f. Exposure to salt air.

g. Operation in damp places or climate.

h. Exposure to steam.

i. Exposure to excessive oil vapor (which may, by condensation and accumulation, change the characteristics of spark-gaps, or be ignited by a spark and produce a conducting flame).

*The limitations of temperature and altitude are adopted for the purpose of uniformity with other standards. Manufacturers consider as standard an altitude up to 1214 meters (4000 ft.).

j. Exposure to excessive dust.
k. Exposure to explosive gases or dusts.
l. Exposure to abnormal vibration or shocks.

Where such conditions exist, it is recommended that they be brought to the manufacturer's attention.

Definitions

28-50 *Lightning.*—Lightning is an electrical discharge* occurring in the atmosphere from cloud to cloud, between cloud and earth or within a cloud.

28-51 *Lightning Surge*†.—A lightning surge is a transient electrical disturbance in an electric circuit caused by lightning.

28-52 *Test Surge.*—A test surge is an electrical impulse of specified characteristics produced for the purpose of laboratory tests.

28-53 *Lightning Arrester.*—A lightning arrester is a device providing a path for electric current between an electric circuit and earth through which, upon occurrence of a lightning surge, current will be conducted in sufficient amount to reduce the over potential of the circuit caused by the surge, and thereafter will cease to be so conducted.

28-54 *Discharge Current.*—The discharge current of a lightning arrester is the surge current which flows through the arrester to earth upon the application to its terminals of a lightning or test surge.

28-55 *Follow Current.*—When surge current passes through a lightning arrester there is formed a conducting path through which generated current‡ may also flow. The generated current which follows the surge current through the arrester in this manner is called the "follow current."

28-56 *Ground* (*Noun and Verb*).—A conducting connection, often accidental, between an electrical circuit and earth, or any other conducting or partly conducting structure or material.

*When such a discharge between cloud and earth terminates on a transmission line, apparatus, or other objects with which we are concerned, it is called a "direct stroke" of lightning.

Although direct strokes may be destructive, they usually strike electrical systems only in the transmission circuits, where, in the present state of the art, it is not economic to protect completely against them. Lightning arresters are not, in general, designed to protect against direct strokes.

†In relation to the circuit as a whole a lightning surge usually takes the form of a traveling wave or transient in space. In relation to any given point of the circuit, however, such a surge manifests itself as a transient in time. A lightning surge manifesting itself as such a time transient at a point in a circuit may be caused by:

1. A direct stroke of lightning at or near the point.
2. A traveling wave caused by a direct stroke elsewhere on the circuit.
3. Release of bound induced charge at the point (as by nearby discharge of cloud).
4. A traveling wave resulting from release of bound charge elsewhere on the circuit.

‡In these standards the current, voltage, and frequency that are supplied to the circuit by the source of power are called respectively, generated current, generated voltage, and generated frequency.

The term "ground" is used loosely, There may be no connection with the real ground or earth. For example, when a porcelain insulator is punctured and a conducting path is formed between the supported line wire and the supporting metallic pin it is customary to say the line is "grounded" to the pin in spite of the fact that the pin may be thoroughly insulated from earth by a dry wooden pole and crossarm. An overhead ground wire is said to be "grounded" to a steel tower although the tower may not be earthed.

28-57 *Earth* (*Noun and Verb*).—An intentional electrical connection or contact with the earth.

Unlike "ground," the word "earth" when used in this sense is an unequivocal term having but the one meaning. Earths are usually made by driving one or more metallic pipes or rods into the earth; by burying metal plates or other conducting material in the earth with suitable connections thereto or by connecting with metallic materials (such as water pipes) already buried in the earth. The resistance of an "earth" depends in general upon the extent of contact with the soil, the degree of moisture present, the nature of the soil and its soluble content.

28-58 *Series-Gap.*—A spark-gap connected in series with a lightning arrester, to keep the circuit through the arrester open under normal conditions and to close the circuit for the lightning discharge by sparking.

28-59 *A Horn-Gap.*—Is a spark-gap equipped with metal horns to assist in interrupting follow current. Such a gap is sometimes used as a series-gap with a lightning arrester.

28-60 *A Protected Series-Gap.*—Is a series-gap protected from rain and other precipitation by a roof or cover.

28-61 *Characteristic Element.*—The characteristic element of a lightning arrester is that part of the arrester whose function it is to control the discharge current, and suppress the follow current.

28-62 *Cathode Ray Oscillograph.*—An oscillograph in which the moving element consists of a pencil of cathode rays. Such a moving element has no inertia and hence can be made to record accurately transients of extremely short duration.

28-63 *Microsecond.*—A time interval of one-millionth (10^{-6}) second.

Classification

28-100 *Classification According to Use.*—Lightning arresters may be classified according to the uses for which they are designed and intended, as follows:

a. As to kind of circuit to be protected; as power or communication type.

b. As to location; as line or station type.

c. As to weather protection; as indoor or outdoor type.

d. As to nature of generated circuit current; as d-c. or a-c. type.

e, As to system connection; as for earthed or non-earthed neutral.

28-101 *Classification as to Control of Follow Current.*—There are two general types:

a. Valve Type: A valve type arrester is one whose characteristic element has a high effective resistance at normal line potential, which resistance decreases with increasing potential and returns to its original value as the applied potential returns to normal. These characteristics result, in general, in suppression of follow current.

b. Follow Current Type: A follow current type arrester is one which permits follow current to flow. Some arresters of this type effect the interruption of the follow current by means of the operation of some current interrupting device, and others by means of the cyclic nature of the generated voltage in combination with some property of the characteristic element.

Rating

28-150 *Rating Defined.*—A rating of a machine, apparatus, or device is an arbitrary designation of an operating limit. Lightning arresters are given voltage ratings only and are rated in terms of generated r. m. s. circuit voltage.

28-151 *System Voltage Rating.*—The system voltage rating of a lightning arrester is the rated r. m. s. system voltage upon which the arrester is intended to be used. This rating will usually determine the general insulation requirements of the arrester.

28-152 *Maximum Voltage Rating.*—The maximum voltage rating of a lightning arrester is the maximum operating r. m. s. voltage to which the arrester should be subjected.* This rating determines the breakdown voltage of the series-gap and the protective characteristics of the arrester.

Characteristics and Performance

28-160 *Characteristics Enumerated.*—The suitability of a lightning arrester for its purpose depends upon the degree in which it possesses three characteristics or properties, *viz.*:

1. Protective ability of which its "protective characteristic" is a measure.
2. Ability to perform its operating cycle.
3. Permanence, involving both its ability to retain its protective ability and to repeat its operating cycle. The measure of this latter ability involves both the frequency and number of such repetitions.

*Since a lightning arrester is intended as a protective device against transient overvoltage, its breakdown voltage is necessarily lower than that of the apparatus it is designed to protect. Its voltage rating, therefore, must have special consideration. Increasing the generated voltage at the terminals of an arrester above its maximum rating reduces its factor of safety and may result in its destruction at the time of discharge. On the other hand, choosing an arrester of a rating above the usual maximum voltage of the circuit to meet abnormally high generated voltage on the system reduces the effectiveness of the arrester as a protective device.

28-161 *Protective Characteristic.*—The protective ability of a lightning arrester under given conditions† depends upon the voltages to which it limits the surge and the times during which it permits such voltages to be maintained. Since protective ability is a function of both voltage and time, it cannot well be expressed by a single quantitative value, but is better indicated by a curve with time and surge voltage as coordinates. Such a curve obtained under controlled test conditions is the "protective characteristic"‡ of the arrester under those conditions, and when obtained under the standard test conditions specified under 28-201 shall be called the "Standard Surge Protective Characteristic" of the arrester.

28-162 *Operating Cycle.***—The operating cycle of a lightning arrester embraces the following actions:

1. At the start of the cycle the circuit through the arrester is open thus permitting no current to flow. (In arresters without series-gaps a very small current may flow.)
2. Upon the occurrence of a lightning surge or other transient potential exceeding a certain voltage the series-gap breaks down and/or the effective resistance of the characteristic element decreases, permitting surge current to pass through the arrester.
3. Surge current continues to flow so long as sufficient surge potential persists and may be followed by generated current—depending upon the type of arrester.
4. Upon cessation of the surge potential, or its reduction to some lower value, surge current

†The ability of a lightning arrester in service to protect apparatus against lightning surges depends in part upon certain conditions external to the arrester itself. Among such conditions are:

a. The characteristics of the incoming surge.

b. The surge impedance of the circuit over which the surge arrives.

c. The number and surge impedance of circuit branches starting at or near the point of connection of the arrester.

d. The length and impedance to surge current of connection from circuit to arrester and from arrester to earth.

e. The distance along all circuit branches between point of connection of lightning arrester and the apparatus to be protected.

f. The characteristics of the apparatus to be protected.

‡The relative effects of the magnitude and the time of application of voltage in causing breakdown of insulation are not as yet definitely known. A "protective characteristic" of a lightning arrester is a measure of its ability to protect against the surge by which it was obtained, but cannot be evaluated in absolute terms until insulation characteristics are better known than at present.

**The successful performance by a lightning arrester of its operating cycle is in no degree an indication of its protective ability which depends upon other characteristics and conditions.

ceases to flow and at some time thereafter the follow current—if present—is interrupted, thereby restoring the arrester to a condition of open circuit.

At the completion of its operating cycle an arrester should be in condition to repeat the cycle immediately, although it shall not be assumed that the cycle may be thus repeated indefinitely.

The performance of its operating cycle should not appreciably alter the protective characteristic of the arrester.

Tests

28-200 The following tests shall apply to all arresters except those with large electrostatic capacity used without series gaps.

Tests for Protective Characteristics

28-201 *Standard Surge Protective Characteristic.*—Tests to determine the standard surge protective characteristic of a lightning arrester shall be made by the use of a test surge, the voltage of which shall be unidirectional and shall rise at the rate stated in 28-202 until the arrester begins to discharge, after which the discharge current through the arrester shall rise at the rate of 100 amperes per microsecond to a crest value of 1000 amperes and thereafter decrease to 500 amperes in not less than 10 microseconds.

28-202 *Rate of Voltage Rise of Standard Test Surge.*—The rate of voltage rise of the standard test surge prior to beginning of arrester discharge shall be as follows:

a. For arresters or arrester sections of low voltage rating up to 11 kv.-100 kv. per microsecond.

b. For arresters or arrester sections of ratings higher than 11 kv. the rate of rise of voltage of the standard test surge shall be increased proportionately, *i. e.*, 200 kv. per microsecond for a 22 kv. arrester, etc.

28-203 *Parts of Arresters to be Used for Protective Characteristic Tests.*—For determining the protective characteristics of low-voltage arresters up to 11 kv. system voltage rating, the entire arrester shall be used (single pole). For arresters of higher voltage ratings tests may be made on suitable sections of the arrester whose combined voltage ratings do not exceed 11 kv., with series-gap set for proportionate sparking voltage, and the results extrapolated.†

28-204 *Other Protective Characteristics.*—Tests for protective characteristics with test surges other than standard may be made, but in every such case the exact characteristics of the test surge employed, including the rate of voltage rise prior to beginning of arrester discharge, rate of current rise thereafter, crest value of current, and duration or rate of decay of current, shall be stated or shown by suitable cathode ray oscillograms.

28-205 *Use of Cathode Ray Oscillograph.*—Protective characteristics of lightning arresters shall be determined by the use of a cathode ray oscillograph.

†In the present state of the art more accurate results can be secured by test on low voltage sections and extrapolating, than by direct test on higher voltage units requiring a voltage divider to use the oscillograph.

Tests for Performance of Operating Cycle

28-210 *Parts of Arrester to be Used.*—Tests for the performance of its operating cycle may be made upon a single pole of the arrester and in the case of valve type arresters of sectional construction may be made upon suitable low voltage sections at proportionate generated voltages and with proportionate series-gaps.

28-211 *Characteristics of Test Circuit.*—The arrester shall be connected across a circuit of voltage equal to the maximum rated voltage of the arrester or arrester section under test and of such power capacity and impedance that the generated voltage across the arrester shall not be decreased more than five per cent below rated voltage for a period of more than one-half cycle of generated current at the crest of the follow current. A non-inductive load, which in the case of higher voltage arresters may be a transformer with loaded secondary, shall be connected across the arrester terminals, so adjusted that generated power current of the order of five to ten amperes shall be flowing past the arrester during the test.

28-212 *Initiation of Discharge.*—Discharge shall be initiated by a test surge so timed as to start follow current as early as possible in a half cycle of generated voltage. If no follow current flows the surge should strike at the crest of the generated voltage wave.

28-213 *Oscillographic Record.*—Voltage and current relations during the period of follow current flow shall be determined by the use of an oscillograph, the electromagnetic type being suitable for this purpose.

28-214 *Standard Operating Duty.*—The standard operating duty of a lightning arrester shall be ten operating cycles at intervals of one minute.

28-215 *Condition of Arrester at Completion of Standard Operating Duty.*—At the completion of its standard operating duty the arrester shall be in the following condition:

a. The breakdown voltage of the series-gap shall not be appreciably altered.

b. The protective characteristics of the arrester shall not be appreciably altered.

c. The arrester shall be in condition to repeat its operating duty, though not necessarily indefinitely.

d. No part of the arrester shall be injured, either mechanically, electrically, or thermally.

Dielectric Tests

28-220 *Standard Test Voltages.*—The standard test voltage for lightning arresters, except as otherwise specified, shall be an alternating voltage having an r. m. s. value as follows:

a. Lightning arresters rated at 600 volts or less—twice rated voltage plus 1000 volts.

b. Lightning arresters rated above 600 volts, 2¼ times rated voltage plus 2000 volts.

28-221 *Duration of Application of Test Voltage*—

a. For insulation consisting of porcelain, glass, or other similar vitrious materials the test voltage shall be applied continuously for one minute.

b. For insulation consisting of wood, paper, fibre, and other similar organic materials, whether or not impregnated, the test voltage shall be applied continuously for 10 min.

c. Standard arresters produced in large quantities for which the standard test voltage is 2500 volts or less, may be tested for one second with a test voltage 20 per cent higher than the one-minute test voltage.

28-222 *Conditions under which Dielectric Tests shall be made.*—

a. For arresters intended for indoor service and for all arresters rated at 600 volts or less, dielectric tests shall be applied with the arrester dry and clean, and at ordinary room temperature.

b. For arresters intended for outdoor service dielectric tests shall be made under precipitation of two-tenths in. (5.08 mm.) per min. at an angle of 45 deg. from the perpendicular with water having a resistivity as low as 7000 ohm cm.

c. When necessary for the protection of the characteristic element during test or in order to attain the test voltages herein named, a portion or all of the characteristic element may be removed during the dielectric tests. In case the characteristic element cannot be removed without also removing its insulating container, dummy container sections of similar characteristics, containing no characteristic element, may be substituted to the extent necessary to carry out the dielectric test.

28-223 *Where Dielectric Tests are to be Made.*—Unless otherwise agreed upon dielectric tests shall be made at the factory.

28-224 *Points of Application of Voltage.*—Test voltage of suitable value shall be applied between the following points.

a. With series-gaps short circuited (and characteristic element removed if necessary—see 28-222 (c)) the test voltage shall be applied between each line terminal and ground, and between each pair of line terminals.

b. With series-gap removed or sufficiently enlarged to prevent breakdown, voltage shall be applied across the terminals of the insulator or insulating material normally in parallel therewith. For the purpose of fixing the test voltage for this test the rated voltage of the insulation in parallel with the series-gap shall be considered to be two-thirds of the generated frequency breakdown voltage of the gap at its normal setting.

c. Insulators so located as to be subjected at any time to only a proportionate part of the voltage between line terminal and ground shall be assumed to be rated proportionately and shall be subjected to proportionate dielectric test voltage.

28-225 *Frequency and Wave-Shape of Test Voltage.*—The frequency of the test voltage shall be not less than 25 cycles per sec. A sine wave shape is recommended. The test shall be made with alternating voltage having a crest value equal to the square root of two times the specified test voltage.

28-226 *Measurement of Voltage.*—The voltage for dielectric test shall be measured in accordance with the section of the Standards entitled "Standards for the Measurement of Test Voltages in Dielectric Tests."

Construction Data

28-250 *Name Plate Markings.*—The following minimum information shall be given on the name-plates of all station and line type arresters for power service.

a. Manufacturer's name and address.

b. Manufacturer's type and designation number.

c. Voltage ratings (system and maximum).

d. Proper setting of series-gap if adjustable.

28-251 *Published Data.*—The following data in addition to information on the name-plate shall be given in manufacturer's publications:

a. Weight.

b. Amount of oil and/or other liquid required (if any).

c. Such dimensions as required for installation.

Current Limiting Reactors

Report of Subcommittee

Two interesting developments in current limiting reactor practise involve the use of reactors which are oil-immersed in steel tanks. One development involves the use of a three-phase reactor, oil-insulated, self-cooled, while the other involves a single-phase unit, oil-insulated, and water-cooled. The advantages claimed for these designs are that foreign material cannot be drawn into the windings and that the equipment can be used with the highest factor of safety either for indoor or outdoor service.

The single-phase equipments are designed for installation as 22-kv. bus section reactors, introducing a reactive drop of 9.2 per cent when passing 90,000 kv-a. No live parts are exposed, as the coil is mounted in a steel tank, and lead covered cable is to be "wiped" to glands bolted to a junction box, which in turn is bolted to the tank. This method of attachment makes possible the removal of the reactor from the circuit without disturbing the "wiped" joints. Each cable terminal is so insulated that cable sheath currents cannot flow through the tank to ground.

The tank is provided with a conservator, pressure relief pipe, oil gage, thermometer, and standard gage trucks.

The magnetic flux of the reactor which would normally link the steel tank, causing large losses, is neutralized by utilizing the copper cooling coils as a short

circuited winding, (the intake and discharge ends of the cooling coils being joined) thus acting as a flux shield. The potential developed in this shield causes a current to flow, which in turn develops an equal but opposite flux. Therefore, no flux enters the tank, and no losses are developed. The material of the cooling coils is a high-conductivity copper tubing of adequate cross-sectional area to permit such currents to flow as will develop the required flux. To neutralize the flux of the reactor coil the current in the shield is limited to a definite value by the inherent reactance of the cooling coils. The losses in the shield are limited by properly proportioning the cross-section of the shield.

Relays

Report of Subcommittee

Three papers have been presented to the Institute during the current year under the auspices of this subcommittee as follows:

Developments in the Impedance Relay and its Application, by H. A. McLaughlin and E. O. Erickson.

Application of Relays for the Protection of Power System Interconnections, by L. N. Crichton and H. C. Graves.

A Carrier Current Pilot System of Transmission Line Protection, by A. S. Fitzgerald.

The second paper listed was presented both at the Chicago and New Haven Regional Meetings.

The work of this year's subcommittee has consisted chiefly of reviewing the work of previous years and attempting to crystalize work which has been started. In this connection attention is called to the matter of standardizing relay acceptance test specifications. A group of last year's subcommittee submitted tentative test specifications in the annual report and expressed the hope that interested engineers would forward their comments to this subcommittee so that a tentative "Standard" could be submitted at this time.

Very few comments have been received and therefore it is thought advisable to submit the recommendation again with modifications herein:

The following acceptance tests are offered for consideration:

1. The complete name-plate data of the relay should be taken, including the name-plate data of its resistor, if it has one.

2. The relay mechanism should be carefully inspected to see that all parts function properly, and to insure that there are no loose screws or other parts.

3. The internal wiring of the relay should be checked to determine that it agrees with the specifications, and that the physical arrangement is satisfactory.

4. Dielectric strength tests should be made between each operating coil circuit and the other circuits grounded to the case, and between the trip circuit and the relay case. Tests should be made at 1500 volts, 60 cycles and should last for one minute.

5. The gap lengths between the various contacts should be measured to make sure that they agree with specified values.

A suggested specification is given below:

Relay type	Minimum allowable gap		
	Main contacts	Auxiliary relay contacts	Lever setting
IA	1/16 in.	....	1 div.
CO	1/16 in.	1/8 in.	1 div.
CR	1/16 in.	1/8 in.	1 div.
IK	1/16 in.	1/8 in.	....
Bellows	1/4 in.	...	....

6. The relay should be operated on all of its taps to make sure that it operates properly and in accordance with specifications.

Some typical specifications are given below:

a. Overcurrent relays should operate within five per cent of the marked tap values.

b. The directional element of directional relays should not move with either current or potential only applied.

c. The directional element of type *I K* power directional relays should operate at 3 volts (across the potential coil, excluding any resistors), 8 amperes (single phase, unity power factor), in 0.40 sec. or less.

d. The directional element of type *CR* power directional relays should operate at 3 volts (across the potential coil excluding any resistors), 8 amperes (single phase, unity power factor) in 0.25 sec. or less.

e. The directional element of type *CR* ground directional relays should operate at 110 volts, 0.5 ampere (single phase, unity power factor), in 0.25 sec. or less.

f. Directional relays should not rebound when the rated voltage is maintained on the relay while 50 amperes are interrupted.

g. Directional relay contacts should stay closed after making initial contact when closing under 50 amperes at rated voltage.

7. The relay calibration curve should be obtained on one tap only. The calibration curve should be carried up to at least five times the pick-up value of the relay. During this test it should also be determined if the relay chatters at the higher current values used. Chattering tests on bellows type relays should be made at 25 cycles, while on induction relays, rated frequency should be used.

8. After Test 7 is completed, the relay contacts should be examined to make sure that there is no pitting. It is sometimes found that contacts

have a tendency to freeze after several operations. In order to make sure that this does not happen, the tripping contacts should be made to make and break currents of values of the order they will make and break in service.

9. Tests should be made to determine that the operation indicator functions with currents of the magnitude available in service.

10. On directional relays the polarity should be checked. On a single-phase, unity power factor test, instantaneous polarity in the same direction on the current and potential coils should cause an *IK* relay to close its contacts, whereas, under the same conditions a *CR* relay should hold its contacts open.

11. Zero torque tests should be made to determine the absence of disk rotation with either potential only, or current only applied to the relay. When current alone is used, a value ten times the minimum tap setting should be used. The zero current test should be made with rated voltage on the potential coil.

12. The volt-ampere consumption and power factor, or the resistance and reactance of the various coils of the relay should be determined. This will determine the burden the relay will impose on its instrument transformers. Burden should be calculated on a 5-ampere basis for current coils, and on a 110-volt basis for potential coils. Measurements should be made at rated frequency.

13. Vibration tests should be made to determine that the relay will not close its tripping contacts when it is subjected to external shock or vibration. During this test the behavior of the operation indicator should also be noted.

14. Heat tests should be made on the relay coils to make sure that they will not exceed the limits specified by the A. I. E. E. Standards. The heat tests on the current coils should be made at rated current. The heat tests on the potential coils of power directional relay should be made at rated potential. The heat tests on the potential coils of ground directional relay should be made at 190 volts, and should last only for five minutes. The reason for this short time test is that under normal operating conditions the potential coils of such relays have no potential impressed upon them, but under conditions of ground, as much as 190 volts may be obtained in circuits whose normal voltage is 110.

15. The effect of ambient temperature upon the relay characteristics should be determined over the range of temperatures likely to be met with throughout the various seasons.

16. The effect of the surrounding atmosphere (excessive dampness, and fumes, etc.) upon the relay characteristics should be determined.

Another item discussed by this subcommittee during the last two years was the matter of name-plate data. In general it is agreed that the following information should be available.

a. Descriptive name of relay.
b. Nominal operating current, voltage, or both.
c. Frequency.
d. Manufacturer's type or style designation.
e. Manufacturer's name or trade mark.

In addition to the above the polarity of directional relays should have studs marked in the same manner as are terminals of instrument transformers. It is further recommended that the following information be available on the card which is usually attached to the relay when furnished.

f. Calibration curve or time setting chart.
g. Volt-ampere consumption and power factor (or resistance and reactance of the various coils).
h. Interrupting capacity of tripping contacts.
i. Resistance values of all resistances furnished with the relay. These values should also be stamped on the name-plate of the resistor.

As questionnaires are unsatisfactory and undesirable, a request is here made for comments on the foregoing.

During the past year many new relay developments have appeared.

The carrier-current pilot protective system has been called to the attention of the engineering fraternity by Mr. Fitzgerald who assures us that this system offers practically all of the advantages of the well tried pilot-wire system without its most undesirable features.

Induction type relays have been developed for use as power-factor relays, temperature relays, for control of reactive kv-a. meters, and for control of street lamp circuits by carrier current. Also a new induction type relay has been developed to perform on the impedance principle for transmission line protection. This relay has its restraining coil designed on the induction disk rather than the plunger principle.

A speed control relay is now used to facilitate the synchronizing of turbine driven generators. It has double-throw contacts operated by Warren synchronous motors through a differential gear in such a way that if one motor is faster than the other, one contact is closed, and, if slower, the other contact is closed. One motor is connected to the bus and the other to the machine being brought up to speed. The contacts control the governor and increase or decrease the machine speed until it corresponds practically to the bus frequency, at which point the machine may be synchronized by another relay or by the operator.

A new polyphase network relay has been developed and along with other things provides a most ingenious method of quickly replacing or testing the relay unit.

Attention has been called to the need of development of relays along certain lines and we set forth below the specific needs which have been mentioned:

1. A multi-contact relay of the plunger type of a size between the present overcurrent plunger

relay and the relay used as an oil breaker closing relay. This device should be either "latching" or "electric release." The contact head should be designed for a complete interchangeability of front and back contacts.

2. A d-c. voltage relay whose pick-up and drop-out values can be accurately adjusted, which will not be affected by a reasonable amount of vibration and whose calibration will not vary by "soaking" or by reversal of potential.

3. Further development of timing relays is suggested as they seem to be the most doubtful. The fan type is somewhat weak mechanically and is limited in length of time. The bellows type is difficult to adjust and will not stay in adjustment as it is easily affected by dirt, temperature, etc. There is considerable distance between the type enumerated above and the expensive motor operated devices. A need is felt for something in between.

4. For automatic transformer stations relays are needed which will measure the total station load. This often results in a requirement for a relay having adjustable back contacts for 50 per cent to 90 per cent of the operating value and having current coils capable of carrying continuously three or four times the operating value. Also these relays should have independent make and break contacts.

5. A reverse current relay is needed having greater sensitivity. For example, it is quite difficult to find a relay which will carry continuously the load current of a generator and yet will operate on the small reversal due to the machine motoring.

6. An impedance relay should be developed for ground protection where the ground current is less than the line load current. Three years ago Mr. W. W. Edson suggested using a *CZ* relay with the voltage restraining element reversed so that it could be operated by the residual voltage of a star-delta potential transformer bank.

Late in the year this subcommittee was charged with the duty developing Standards for Relays and the preliminary draft of September 1923 was resurrected to be worked over. This work has been started but the best that can be hoped for is to have a suitable foundation laid down for the successors of this subcommittee next year.

Along with this to the successors of this subcommittee is recommended:

1. A study of the operating experience due to the use of low-tension potential transformers for relaying high-tension lines where the voltage vectors are not an exact reproduction of what is taking place in the lines protected. The various compensator arrangements are too complex to be 100 per cent reliable.

2. Further study in the matter of relaying a transmission system having two parallel lines which may work in parallel or independently. Various cross-connected schemes will meet the parallel condition but they fail on the second. Pilot wires would be suitable but they are expensive. Impedance relays are not suitable for short sections of lines and they require special consideration when the expected ground currents are less than the load currents.

3. A study of the operating experience in the use of polyphase versus single-phase directional relays.

It is recommended that technical papers be obtained for presentation to the Institute of the three subjects named above.

F. L. HUNT, *Chairman.*

Discussion

K. B. McEachron: In setting up standards for determining the protective characteristic of lightning arresters two points of view must be considered. First, what kind of duty is imposed by the surges which can come along connected circuits, and second, what can be produced and measured in the laboratory.

It seems probable based on field studies that voltages of the order of 2,000,000 volts may be reached in times of the order of 1 to 10 microseconds. The minimum time may be somewhat less and the maximum somewhat more than that given as no accurate measurements are yet available.

For a 220-kv. arrester this means, assuming 1 microsecond as the time to rise, a rate of voltage rise of 2,000,000/20 or 100 kv. per microsecond for each 11 kv. of rating. This it will be noted is the rate given in Section 28-202. Assuming, however, that the same potential gradient exists over an 11-kv. line half as high above the ground as the 220-kv. line, then the rate of potential rise will be 1000 kv. per microsecond or ten times the rate of voltage rise on the 11-kv. arrester as for the 220-kv. arrester when the transmission conductor is in the same electrostatic field.

It is feasible in the laboratory at the present time to produce impulses rising at the rate of 100 kv. per microsecond, but it is not feasible to produce impulses rising at the rate of 1000 kv. per microsecond, and yet have the wave front reasonably free from large oscillations.

If tests were made involving only potential rise, a wave rising at the rate of 1000 kv. per microsecond or 100 kv. in 0.1 microsecond might be obtained reasonably free from oscillations, but arrester testing requires the production of large currents in very short spaces of time which is not a condition conducive to steep rates of potential rise without excessive oscillations.

The traveling-wave theory states that the current in the traveling waves reaches its crest value at the same time that the voltage reaches its crest value. Going back again to the 220-kv. transmission line,—if the surge impedance be taken as 500 ohms and the arrester resistance also be considered as constant and equal to 500 ohms, then the current traveling in the conductor and through the arrester rises to a crest value of 2,000,000/500 or 4000 amperes in 1 microsecond. This assumes that the traveling wave has a crest potential of 2000 kv. and that the arrester is at the end of the line with no branch circuits.

In the present state of the art it is not possible to obtain a

rate of current rise even approaching a figure of 4000 amperes per microsecond and still maintain reasonable freedom from oscillations and be able to record the phenomena on the oscillograph. To obtain such rates of current rise means little or no resistance in the circuit and very small inductance. Such a decrease in resistance means serious oscillation.

It seems desirable, therefore, to arrange the surge so that a current which is measurable and which can be obtained without excessive oscillations be chosen, and 100 amperes per microsecond seems about as high a rate as present methods and technique will allow. The crest value of 1000 amperes may in my opinion be subject to some variation, as for instance plus or minus 10 per cent, but the current should not decay too fast and the specification that the current shall decay to 500 amperes in a time not less than 10 microseconds is not unreasonable.

To specify a voltage wave when testing arresters is not sufficient because this only determines the breakdown voltage of the arrester. The second phase of arrester operation depends on the rate of current rise, the maximum current, and the duration of the current.

Since this is true it seems that the proper comparative test is to apply the same rate of potential rise, the same rate of current rise, and the same maximum current to all arresters, allowing the potential during this current flow to vary depending on the arrester itself and not on the impulse circuit to which it happens to be connected.

If impulse tests are to be made on insulation it is only necessary to consider rates of potential rise and a wave specified on the basis of maximum potential and time required to reach this potential would be sufficient as long as the breakdown occurs on the front of the wave. For such a test it would probably be desirable to specify also an exponential voltage rise.

For arrester testing such a specification is not sufficient. The maximum value of open circuit potential of the applied wave is not important. With the arrester the rate of voltage application up to the time when current begins to flow through the arrester is important, but what the voltage would have been if the arrester had not broken down has little or nothing to do with the characteristic of the arrester after it did become conducting. The remainder of the arrester performance after becoming conducting is dependent on the current-time relations. Thus sphere-gap measurements are not enough for the proper determination of the arrester characteristics, and I believe that it is a distinct step forward to specify the use of the cathode-ray oscillograph for the accurate determination of the arrester characteristics with respect to voltage, current, and time.

The manufacturer of lightning arresters does not make a practise of conducting complete tests such as outlined in the proposed standards on all arresters. Such complete tests are made on all new designs but it is felt that to take cathode-ray oscillograms, for instance, on all arresters would make an unnecessary addition to the cost of the arresters.

The proposed standards do give the user of lightning arresters a set of standards which when applied to arresters will allow him to make comparisons on a common basis which he has not been able to do in the past.

Automatic Stations

ANNUAL REPORT OF COMMITTEE ON AUTOMATIC STATIONS*

Introduction

THE Committee on Automatic Stations was appointed by the Board of Directors, April 8, 1927. This, its first annual report, will give a general description of automatic station development during the past decade, and will enlarge upon some of the more important new features brought forward during the past year. Research, operation, standards, bibliography, and suggestions for future study will each receive attention.

Scope

Broadly, the scope of work is comprised under automatic generating stations; automatic substations; and automatic station auxiliaries and the committee has complete jurisdiction over the apparatus that is associated with such installations and in the building or enclosing housings. Successful installations demand proper ventilation, temperature and moisture surveys, and with these, in addition to the various auxiliary apparatus associated with the control, the committee is concerned.

Research

Research has been carried forward by operating and manufacturing companies with assistance rendered by several universities. The principal studies have been concerned with the operating requirements of devices for various classes of service. The number of cycles of operation per year for some of the more important devices has been determined.

Overcurrent relays, differential relays and other similar protective relays operate through about 300 or less cycles per year. Overcurrent circuit breakers in railway service may operate through as many as 1000 cycles per year. Load-limiting resistors may be introduced into circuits by the operation of their short-circuiting devices from 500 times per year in Edison Service to 100,000 or more times per year in interurban railway service. Regulating relays may be called upon to operate between 1,000,000 and 30,000,000 cycles per year. Other devices may be called upon to operate between the limits as given for overcurrent relays as an average minimum and regulating relays as an average maximum. Each application, particularly to automatic station service, requires a full knowledge of operating requirements in order to derive a maximum benefit from the particular device in its particular service.

Another field of research has been in the determination of the minimum protection required for various classes of power apparatus in automatic stations. The results of these studies are given in the Standards for Automatic Stations recently approved by the Board of Directors. Still another field for research has been in the study of operating conditions and requirements so that the automatic stations might be designed along simpler lines to give greater reliability and continuity of service. Valuable assistance has been rendered to the manufacturers by the engineers of operating companies. Several papers were prepared and presented by these engineers describing their experiences with automatic stations. This has stimulated the manufacturers toward the development of less complicated devices which give more reliable operation and permit better service to be rendered by public utilities.

Development

Development has been directed toward simplifying operating sequence, reducing the number of devices required for various classes of equipment, and making the operation more positive and reliable. Controls have been developed recently for power rectifiers. A brief description of the outstanding features of these designs is given later.

Supervisory systems for the control of remote power apparatus have reached a high state of development. Several papers indicating the trend of this development have been presented to the Institute. Many refinements have been incorporated and these systems are now considered to have an important field of application.

Telemetering is new. Only about a dozen systems including it are in service. Operating experience is needed. The state of development has not yet been passed. Several systems now being offered are simpler and more reliable than the older ones. They indicate that this important adjunct for automatic stations may soon be incorporated in standard designs.

Power Rectifiers

Power rectifiers are the latest type of power conversion apparatus to be used in automatic stations. These differ from the usual rotating power apparatus in that they have no inherent mechanical moving parts. They differ from the usual static power apparatus in that they require auxiliary features which have mechanical moving parts.

The power rectifier employing mercury is a static converter with a moving arc stream. The load responsive starting and stopping features of the control

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resemble those used for rotating synchronous converters. The methods used for starting and for stopping, and the protective measures resemble those used with static transformers having artificial cooling. Several features, however, are peculiar to the power rectifier. They are: (1) the rectifier must be ignited and (2) a relatively high vacuum must be maintained.

Ignition of the rectifier is accomplished by a moving auxiliary electrode. Some schemes use alternating current for the arc starting. Some use direct current. When alternating current is used for ignition, two additional auxiliary starting electrodes are required. The ignition equipment is fully automatic. It starts the arc as soon as a-c. power is available. It extinguishes the starting arc as soon as the power arc is formed and maintained. It will re-ignite the rectifier automatically if for any reason the power arc is extinguished.

The required vacuum is usually maintained by two pumps. One is a rotary motor driven oil sealed mechanical pump; the other a mercury condensation pump. These start and stop in response to vacuum conditions as indicated by a vacuum relay.

Water cooling systems are usually favored for preventing the rectifier temperature rising above a specified maximum. It is controlled by conventional thermal relays connected in the operating sequence of the automatic switching equipment.

The minimum protection recommended for power rectifiers is less than that recommended for synchronous motor generators and synchronous converters, but is greater than that recommended for static transformers, synchronous hydroelectric generators, and synchronous condensers.

Protection against a-c. undervoltage, single-phase starting, and single-phase operation is sometimes required for power rectifier auxiliaries under certain conditions. Protection against severe a-c. over-current is generally required. It may be self-resetting in the case of power rectifiers, while it is usually of the lock-out type for rotating machines. This is due to the difference in the inherent characteristics of the two machines. Protection against d-c. reverse current and excess temperature due to sustained overload is provided for the power rectifiers just as for rotating power apparatus. Power rectifiers, unlike most other types of power apparatus, are usually provided with protection against poor vacuum, failure of vacuum pump, and failure of cooling fluid supply.

The starting and stopping of power rectifiers in automatic stations follows the same principles as developed for rotating machines. Some device substitutions are made in the protective circuit to suit the individual characteristics of the rectifiers. Similarly, load-limiting and load-shifting features may be provided just as for rotating machines, particularly synchronous converters.

In general the automatic control for power rectifiers is similar to that for rotating machines, excepting where it has been necessary to develop some special devices to suit the peculiar characteristics of the rectifiers just as it was necessary to develop special devices for some of the peculiar characteristics of synchronous motors, d-c. generators, synchronous converters, and other types of power apparatus.

Supervisory Equipment

Supervisory equipment is rapidly assuming an important place in the design of electric power systems. It is being used not only for the supervision of automatic stations, but for the supervision of important power distribution networks and the operation of large substations and generating stations. The trend is definitely toward a simple system normally at rest. Any operation either to actuate a device or to report an actuation starts a sequence. This usually continues until the operation and report are completed. Then the system remains at, or returns to, a position of rest.

Three or four line wires continue as standard for supervisory systems with visual indication of operation and the usual operating currents and frequency. Carrier-current systems use either one or two wires, or, in some cases, are superimposed on power circuits. Each method has a field of application depending upon local conditions and operating requirements.

Several designs of supervisory equipment use the ordinary telephone apparatus and telephone communication circuit for both talking and control, as well as answer back. These have a relatively restricted application.

Reliability of supervisory systems and equipment is only as good as the line wires which are provided. The terminal apparatus may be perfect. It may operate precisely as the designer intended it to operate. Yet, if the wires connecting the terminal equipments fail, the entire system is rendered inoperative. It is necessary that this feature of supervisory equipment be taken into account in its application, since it has shown a definite limit for such systems under present day operating conditions.

Telemetering

Telemetering is just coming to be recognized as a distinct necessity in the operation of automatic stations, particularly those forming part of large electricity supply systems. Developments have been rapid during the past two years. A number of systems is on trial, most of them too elaborate for economical application. Some give promise of meeting the requirements of high accuracy, low cost, reliable operation, and freedom from resistance and other circuit errors.

The telemetering systems now in operation are used for a very wide variety of purposes. Some give readings of circuit current and voltages. Some give readings of station load. Still others are used for transmitting to a central office, the readings of total station loads, and also for again totalizing all the stations on a system and returning this total to each of the contributing stations.

Still other systems are used for giving a central dispatcher knowledge of the distribution of demand over a given system. Others serve to adjust the supply of power from two sources in proportion to the load demand required from these two sources.

In another year, operating experience should be available which will permit a better picture of the trend of this very interesting development to be given more definitely.

Carrier Current

Carrier currents in frequencies from 500 cycles to over 50,000 cycles are being used for the operation of supervisory and telemetering systems. Some of these are used in combination with automatic stations. Some are used for the operation of power apparatus in remote stations. Several papers have been presented to the Institute on this subject and the discussion of these papers gives the trend of thought. A great deal of research and development work is being done on this subject and future reports will no doubt be able to give more comprehensive data concerning it.

Operating Experience

Operating experience, particularly that with automatic stations, has formed the subject of several papers presented before the Institute. The art would advance very much more rapidly and more surely if more operating engineers would take it upon themselves to present to the membership, through papers read at regional meetings, their individual experiences with automatic stations. The manufacturers and designers recognize that each power system has its individual characteristics. These require the fitting of automatic stations, individually to each power system. Notwithstanding these facts, all systems have a certain similarity. They also have certain operating requirements. The art is handicapped because the designers do not obtain freely from the operators the system requirements and performance under given conditions. A number of the operating engineers have contributed richly toward the development of the art by telling of their experiences. It is believed that a broadening of this idea will do much to stabilize the industry.

Maintenance and Inspection

Maintenance and inspection of automatic stations are prime requisites for their successful operation. To obtain a maximum benefit from these stations it is necessary that they be given adequate, systematic, and intelligent inspection. The word "intelligent" really covers the field, for, in a broad sense, it includes the words "adequate" and "systematic."

Much of the development work carried on by the manufacturers has been with the idea of reducing the necessity for maintenance and inspection to a minimum. The devices and schemes of operation which have been produced from this development render the automatic station a unit in any system, which not only contributes to the economic operation of that system, but which also does much to promote continuity of the service supplied by that system.

Practical analysis verifies the statement that "Nothing is perfect." Any commercial device is a compromise between perfection and cost. The quality of service to be expected is thus necessarily a measure of the maintenance required to affect those things by which a device or an equipment as a whole fall short of perfection. If the outage of a unit is not a serious matter, time may be allowed for clearing a failure in the switching sequence. This would normally render the unit inoperative under certain conditions; hence there might be a tendency to neglect the matter of routine inspection or maintenance.

In protective devices, however, the failure which might result in costly damage as well as extended outage is a far more serious matter. For this reason, the automatic station is safeguarded by protective devices not ordinarily found in attended stations. In protecting against equipment failure, one protective device is often reenforced by another, so that only by simultaneous failure of separate and independent protective devices can serious damage be done to the equipment. These protective devices are the product of many years of research, development, and experience. It is necessary, however, that they be used intelligently. They must be suitably adjusted and adequately maintained if it be expected that they render the service for which they were intended.

The importance of continuity of service renders the proper functioning of switching sequence of equal importance with that of protective equipment. A knowledge of the proper functioning of each device and its relation to other devices is the first qualification for one responsible for the inspection or maintenance of an automatic station. Such an individual need not be a technically trained man; in fact, often he is not. He should, however, have a thorough grasp of the fundamentals, and have experience not only in the operation of the equipment itself, but in the relation of the station to the rest of the system. The latter is essential if he is to be able to analyze properly the limitations of the equipment and make adjustment of it accordingly.

With each equipment the manufacturers usually supply instruction books and diagrams giving a comprehensive analysis of the scheme of operation, as well as detailed information of each device. If he is to give the station the best attention an inspector, or maintainer, should be thoroughly familiar with the contents of the instruction book and wiring diagram.

Sometimes the maintainer overdoes his job in such matters as cleaning and filing of contacts. Relays are usually under covers. Inspection of the parts is facilitated by the use of glass, making the removal of the covers necessary only at infrequent intervals. The removal of oxide from contacts is accomplished by the use of crocus cloth, or cleaning with carbon tetrachloride. Contacts in the power circuits and the heavier duty

control circuits, when properly adjusted, will require little or no dressing of the contacts. They should be kept clean and bright. Filing is usually not required, as the contacts wear naturally to better surfaces than may be effected by filing. Unless carefully done, filing tends to make matters worse, and even shortens the life of the contact.

Judicious lubrication of moving parts, cleanliness, and the keeping of wiring connections and interlock adjustments tight are the principal factors having to do with the proper maintenance and inspection.

The frequency of inspection of any particular station is best determined by those in responsible charge of the systems. The experience of others in the operation of similar equipment in like service may be used as a guide, but seldom serves as a standard to be followed, since operating conditions are never identical. A brief experience with an inspection schedule will determine where it should be modified so as to give best results. An inspection report made in preliminary fashion with mimeograph copies might well be used during the the first few months until a definite plan is decided upon. Samples of inspection report forms used by a number of operating companies are now available and may be had upon request from them.

A summation of the situation is given by a member of the committee who has had a number of years of experience in the operation of automatic stations. He states that several years of experience with daily inspection, not having a definite routine, did not produce the required results. Railroad equipment is operated on a car or locomotive mileage basis as determined by the conditions. It is then taken into the shop, thoroughly overhauled and sent out on the road subject to a trip of casual inspection somewhere on the road, until it has operated a certain mileage. Then it is returned again to the shop for general inspection. It is logically assumed that after such an inspection, it should cover a predetermined number of miles without attention. The same assumption can be accepted for the inspection of automatic station equipment. There should be a periodic thorough inspection; weekly on some parts of the equipment and monthly, semi-annually, or annually on other parts. Rotating equipment may have to be cleaned at intervals of two or three days,—or even longer,—depending upon the number of hours run and conditions of ventilation of the station. The station may have to be visited daily for other reasons than inspection of apparatus where no supervisory equipment is used. With supervisory control, no other attention should be needed than cleaning and periodical inspection.

Standards

A final report on Standards for Automatic Station No. 26 was presented to the Standards Committee at its January 20, 1928 meeting. Following a letter ballot, this report was submitted by the Standards Committee to the Board of Directors with the recommendation that it be approved as an A. I. E. E. Standard. The Board of Directors approved the Standards for Automatic Stations, April 6, 1928.

The Committee on Automatic Stations intends to present revisions of these standards to the Standards Committee from time to time as the necessity for them may arise.

Functional Numbers

Functional numbers have been used for automatic station devices and functions for about 15 years. A gradual standardization has resulted. The latest list is given in the Standards for Automatic Stations recently adopted by the Board of Directors.

The functional numbers initially followed the sequence of operation of the devices. Later, as automatic stations developed, this sequential numbering could not be followed. It resulted in an arbitrary numbering system which has become generally known in the art.

The present numbering system uses a base of not more than two digits. The numbers from 1 to 99 inclusive cover the entire range of basic functions. Numbers in the 100, 200 and other series are used for designating these functions when used with feeders, supervisory systems and the like. The system of numbering the functions, however, still remains arbitrary.

It has been thought that a system of numbering more logical and less arbitrary might be developed. A subcommittee has had this matter under consideration since December 1, 1927. They have rendered several reports. Progress has been made, but a solution has not yet been supplied. It is recommended that a subcommittee be appointed to continue the study of this important topic during the ensuing term.

Papers

Papers presented under the auspices of, or in cooperation with, the Committee on Automatic Stations during the current year have been as follows:

Subject	Author	Place & Date
Operation and Performance of Mercury Arc Rectifiers.	Caesar Antoniono	Chicago–Nov. 1927
Automatic Control of Edison Systems................	O. J. Rotty & E. L. Hough	New York–Feb. 1928
Automatic Switching of Incoming Lines and Transformers.................	A. E. Anderson	St. Louis–March 1928
Mercury Arc Rectifier Substations................	G. E. Wood	New Haven–May 1928

Unfinished Business

Topics which have been under consideration by the committee and concerning which no report has been rendered are as follows: (1) Ventilation; (2) Fire protection; (3) Economical construction; (4) Unusual operation conditions; (5) Load dispatching; and (6) Wire designations.

In addition to these items of unfinished business, there are other items upon which reports have been rendered but which do not fully close the subject. These are as follows:

(1) Papers, (2) Standards, (3) Research, (4) Operation reports, (5) Remote metering, (6) Supervisory control, (7) Progress in the art, (8) Inspection, (9) Functional numbers, and (10) Bibliography.

It is recommended that these subjects be given consideration by the succeeding committee.

BIBLIOGRAPHY

Many requests have been received from time to time for a bibliography on automatic station literature. Such a bibliography has been prepared and forms an appendix to this report. It is recommended that future committees add to this bibliography so that there may be found available in the TRANSACTIONS of the Institute a comprehensive bibliography on the subject.

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General Power Applications

ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS*

To the Board of Directors:

Your Committee on General Power Applications endeavored to perform the following functions:

1. Keep in touch with all developments relating to general power applications.
2. Foresee the need for development of new electrical apparatus to meet new conditions in general power applications.
3. Develop papers to be presented before the Institute on subjects relating to general power application.
4. Present a report at the end of the Institute year recording the development of general power applications during the preceding year.

To accomplish the first function, a review of the technical press was undertaken, each committee member being asked to review certain periodicals. To be successful, a review of this type requires the sacrifice of considerable time from our daily occupations and is not extremely fruitful in results even if such review is punctiliously observed. However, we were fairly successful in this endeavor.

The second endeavor mentioned above is the hardest of all to attain but is one which, if successful, would add much to the value of the committee.

The third endeavor has brought out many suggestions for prospective papers. These include the following:

High Cycle Equipment for Portable Tools.
Telephone Central Office Power Plants.
Short Circuit Protection for Industrial Installations.
Overload and Single Phase Protection for Across-the-Line Squirrel-Cage Induction Motors.
Application of Power and Control Equipment to Power Plant Auxiliaries.
Across-the-Line Starting of Induction and Synchronous Motors, Including 2200 Volt Application.
Improvement of Ward Leonard Control with Special Reference to Application to Elevators.
Mass Production of Electric Light Bulbs.
Storage Batteries, Improvements and Applications.

Instead of enumerating a large number of new applications, only representative ones are cited in this report. Details of these are more specific than formerly and we feel that in drawing these to the attention of the membership, we shall have focused their attention on the general trend of all applications. Necessarily, there are many types not mentioned, either because the committee has no access to such, or because their application is somewhat similar to others.

The thanks of the committee is extended to the Allis-Chalmers Mfg. Co., American Telephone & Telegraph Co., Bethlehem Steel Co., D. H. Braymer Equipment Co., Canadian General Electric Co., Century Electric Co., Consolidated Gas, Elec. Lt. & Power Co. of Baltimore, Cutler-Hammer Mfg. Co., Duquesne Light Co., Edward Ford Plate Glass Co., Electro-Dynamic Co., General Electric Co., Graybar Electric Co., Howell Electric Motor Co., Lincoln Electric Co., Louis-Allis Co., The Management Engineering & Development Co., Ohio Bell Telephone Co., Philadelphia Electric Co., Reliance Electric & Engineering Co., Stone & Webster, Westinghouse Electric & Mfg. Co., J. D. White Engineering Co., the Universities of Missouri, Massachusetts Institute of Technology, Purdue and Toronto, firms with which committeemen are connected or whose cooperation and publications we have made use of in compiling this report.

Marine Equipment

At the close of the year 1927, there had been placed in commission, or were under construction, a total of 118 electrically propelled vessels of various types, ranging from river towboats and small yachts to the largest types of sea-going ships. The equipment of these crafts aggregated more than 700,000 shaft hp., about 92 per cent of the primary power being supplied by turbines and 8 per cent by Diesel engines.

The outstanding event of the year was the completion and installation of turbine-electric propelling equipment for the Panama Pacific Liner *California*, Fig. 1, the largest passenger ship ever built in the United States and the largest electrically driven ship of her class in the world. The *California* is a twin-screw ship with a displacement of 30,250 tons at load draft.

The maximum energy delivered to her propeller shaft is 17,000 shaft hp. and a speed of 18 knots can be maintained with this power input. At the cruising speed of 16.5 knots, the output of the turbo generator is 13,500 shaft hp. and at this speed the ship has a cruising radius of 15,400 mi.

The propelling equipment comprises two 16 stage steam-turbo generators, each having a maximum capacity of 6600 kw. at 2880 rev. per min. This power is transmitted to the propeller shafts by means of two synchronous induction type motors having a continuous maximum rating of 8500 shaft hp. at 120 rev. per min. These motors are direct connected to

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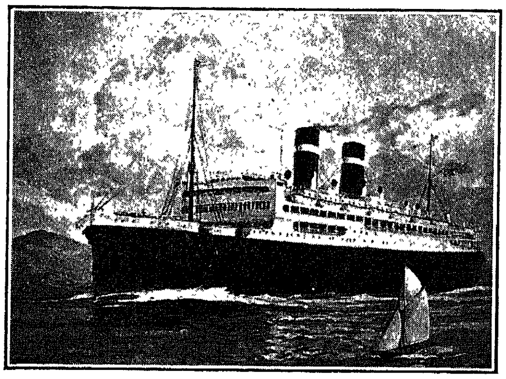
Presented at the Summer Convention of the A. I. E. E., at Denver, Colo., June 25-29, 1928.

the propeller shafts and are reversible so that no reversing turbines are required. Both propelling motors can be operated at about ¾ of their rated output by the current supplied from one of the two turbo generators, thus insuring economical cruising at reduced speed.

The *California* was launched October 1, 1927 and work on a second ship of the same size, to be provided with electric propelling equipment of the same power, is already under way.

Diesel Electric. While the primary power supplied by Diesel engines is comparatively small compared to



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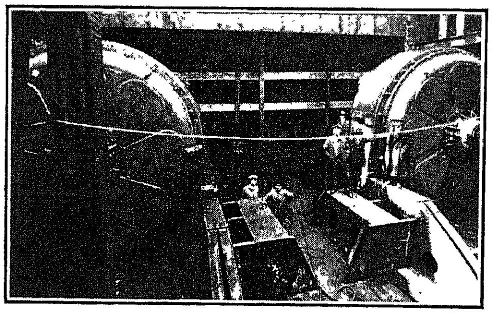

B

FIG. 1—A. TURBINE-ELECTRIC-PROPELLED LINER *S. S. California*

B. VIEW SHOWING THE INSTALLATION OF THE MAIN PROPULSION MOTORS

that supplied by steam turbines, yet there have been a number of notable applications of Diesel-Electric Drive for marine work.

One of these in which d-c. apparatus is used is the Coast Guard Cutter *Northland* which is now serving on patrol in Alaskan waters.

The main engine room equipment consists of two Diesel engine-driven generators, each rated 410 kw. 250 volts at 200 rev. per min. These supply current to a double-unit type, shunt-wound propeller motor, Each section of this motor (Fig. 2) is rated 500 hp. at 120 rev. per min. The ship will develop a speed of 12 knots with her single propeller operating at 120 rev. per min. and the motor developing 1000 shaft hp. The control is located in the engine room and is of the variable voltage type.

There are some unusual features in the propelling equipment, one of them being the use of a magnetic clutch between the motor and the propeller shaft. Under normal conditions the motor and shaft are rigidly bolted together, but when cruising at reduced speed in the ice fields the bolts will be removed and the power transmitted through the magnetic clutch. This will transmit a torque equivalent to 500 shaft hp. at 95 rev. per min., but any increase of load beyond this rating will cause the clutch to slip and will thus prevent dangerous stresses.

Other applications of Diesel-Electric Drive include that on four large double-end Diesel-electric ferry boats made for the Southern Pacific Company for

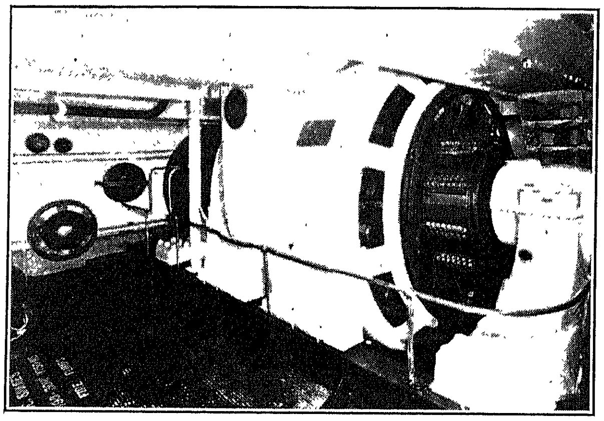

FIG. 2—U. S. COAST GUARD CUTTER *Northland's* 1000-HP., 120-REV. PER MIN., 500-VOLT DOUBLE ARMATURE PROPELLER MOTOR

service in San Francisco Bay, electrically propelled packet boats running between points in and around New York Harbor and cargo boats recently open to Diesel electric propulsion by the U. S. Shipping Board. Another novel application of Diesel-electric drive was inaugurated by the Bureau of Light Houses by its decision to adopt this method of propulsion for three new light ships. These ships are at anchor most of the time but in severe weather, the propulsion equipment will be used to take the strain off the anchor chains and to maintain the position of the light in the event of the breaking of the moorings.

U. S. Navy. The Washington Arms Conference in 1921 served to greatly emphasize the consideration of the relative value of weight and space for power apparatus on board ships. Recent designs of machinery have shown a marked advance over previous practise in the matter of lightness and compactness without sacrifice of strength or reliability. This has been made possible by the use of light metal alloys and the use of fabricated steel parts to replace the original cast

iron parts. Cast iron is not only too heavy a construction, but is also unreliable under such shocks as are imposed by battle conditions. The chief developments in application in the past year have been along the lines of building machines to meet the peculiar needs of the application.

A notable application is that of a 200-hp., 5000-rev. per min. d-c. motor on which the Navy Department has recently completed tests. This motor is used to drive a three-phase blower type compressor having a capacity of 3200 cu. ft. and a discharge pressure of 10 lb. Special precautions had to be taken to balance this armature, the peripheral speed of which is approximately 20,000 ft. per min. The bearings are flood-lubricated, the oil being supplied by a separate motor-driven pump. The method of cooling is novel, the cooling air being that which is drawn through the motor into the first stage of the compressor.

Electric Railways

The applications in the electric railway field were concentrated mainly upon the modernization of rolling stock. Existing cars were replaced with equipment better suited to modern transportation requirements, including motors and control of the latest design.

Oil-Electric Locomotives. Interest in the application of oil-electric locomotives continued throughout the year and a number has been put in service. These demonstrate the economies and other operating advantages of this type of drive. Two 100-ton units are now in heavy switching service on the Erie Railroad and 60 ton units were completed for the Chicago & Northwestern Railway, the Union Carbide Company, and the American Rolling Mills Company. Work is also proceeding on oil-electric, freight and passenger locomotives for the Putnam Division of the New York Central Railroad and a 300-hp. oil-electric motor car is ready for service.

Gas-Electric Motor Cars. One of the large automotive truck manufacturing concerns has recently announced the completion of car units consisting of gasoline engines and electric generators, to be used with an electric drive to furnish power for virtually any kind of transportation. This is unique in that a single base contains all the power equipment and accessories except the gasoline tank, the radiators and such electric motors as may be used in driving the axles. An important application is expected to be railway transportation. More than one power unit can be used, ranging from a single day coach moving along the rails without the help of a locomotive, to a six-car commuter train in which the cars at each end of the train contain power units. By means of a system of remote control, these units can be operated by an engineer at either end of the train.

Special Type Locomotives. A new combination trolley and storage battery type of locomotive has recently been placed in service by the Chicago, North Shore and Milwaukee R. R. These locomotives may be used either on the trolley system, or on tracks not now equipped with trolleys. The motors are ventilated by electrically driven fans. D-c. control is provided for either trolley or battery and transfer from the trolley to the battery power is automatic. Motor-generator sets are used for charging the battery when running from the trolley.

Automatic Substations for Railway Signaling Power Supply. The continuous inductive type of automatic train control provides a new field for the application of small frequency-changing motor-generator sets and automatic control for starting the sets and for connecting the generators to the load in the shortest time possible. Power is supplied to the train control system at a frequency of 100 cycles in order to eliminate inductive interference from commercial circuits.

Motor-generator sets provide the 100-cycle power from 25 or 60 cycle primary sources. The motor-generator sets range in size from 1.5 kv-a. to 60 kv-a. The rating depends primarily upon whether the power

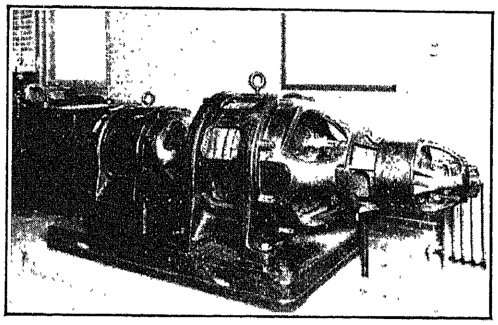

Fig. 3—Motor Generator Set

is to be used for both automatic train control and automatic block signaling or only for the former.

A very interesting installation of automatic substations to provide 100-cycle current for the operation of both automatic block signaling and automatic train control is on the Pan Handle Division of the Pennsylvania R. R. system between Pittsburgh, Pa. and Newark, Ohio. This division consists of 158 route mi. or 375 track mi. Eight automatic substations are provided, the maximum distance between any two adjacent stations being 36 mi. and the minimum five miles. Each station, excepting one, contains a 60-kv-a. 80 per cent power factor, 220-volt, single-phase, 100-cycle alternator, with direct connected exciter, driven by a direct connected 75-hp., 220-volt, three-phase, 60-cycle, squirrel-cage induction motor with the necessary automatic switchgear. Fig. 3 shows one of the seven motor-generator sets and Fig. 4 shows one of the automatic switchboards. The motor starter is in the foreground, next are two feeder panels, one to feed east and the other to west. Next is the relay panel followed by the voltage regulator panel. The panel in the back-

ground is for the control of the two motor-driven air compressors in the extreme background and is not part of the automatic switchgear.

Mining Industry

A new type "sealed equipment" cable-reel-gathering locomotive has been provided for mine application and is provided with two 30-hp. motors, contactor control of the progressive series parallel type, and a motor-driven cable reel with 450 ft. of double-conductor, concentric, rubber-covered cable.

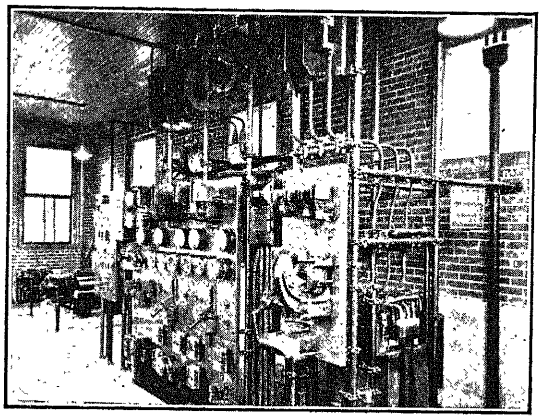

Fig. 4—Automatic Switchboard

The traction motors, the cable-reel motor, cable-reel collector rings, control, headlights, and all parts of the equipment with the exception of the trolley pole and the reel cable are completely enclosed in strong cases which are designed to prevent any gas explosions that occur within these cases being transmitted to the surrounding atmosphere. With the exception of short sections of cable leading to the motor, where flexibility is necessary, all wiring is enclosed in rigid type conduit, securely anchored and provided with steel fittings where it enters the various compartments. Flexible motor cables are enclosed in heavy rubber hose, the ends of which are also provided with steel fittings; Figs. 5 and 6 show views of this type of locomotive.

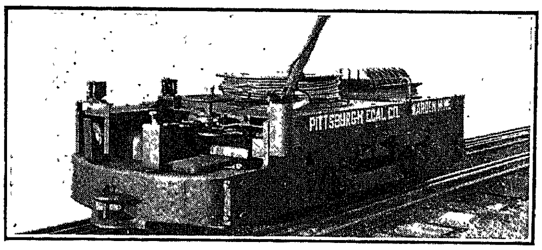

Fig. 5—Electric Mine Locomotive

Quarry Locomotive Cars. An interesting system of remote control for locomotive cars operating on quarry tracks was developed. With this system a single operator, located in the tower-control station, from which he can see all the cars, is able to start, stop, and even to switch cars on different tracks. Electrical equipment of the cars consists of high-torque squirrel-cage motors provided with solenoid brakes and controlled through a pair of reversing contactors which throw the motors on the line at full voltage. Two current-collecting shoes are used for making contact with two "third rails" located between the traction rails. The separate tracks on which these cars operate have isolated circuits or the cars can be maneuvered on a loop track with isolated sections.

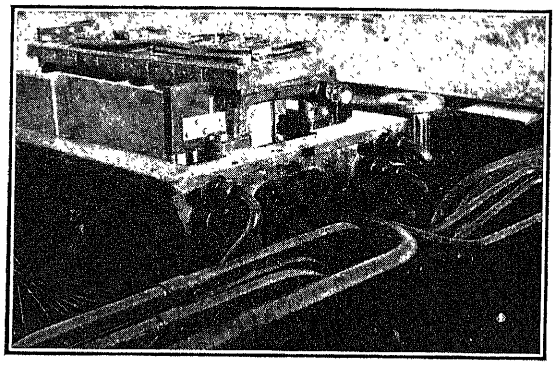

Fig. 6—Interior View

The control operator handles the cars from a pilot switch which actuates the reversing contactors and, when the current is shut off, the solenoid brakes set automatically and retard the car, torque being adjusted for smooth retardation. The application of this system is expected to speed up production and reduce operating cost, inasmuch as one operator can in this way handle several cars whereas with the old system an operator was required for each car.

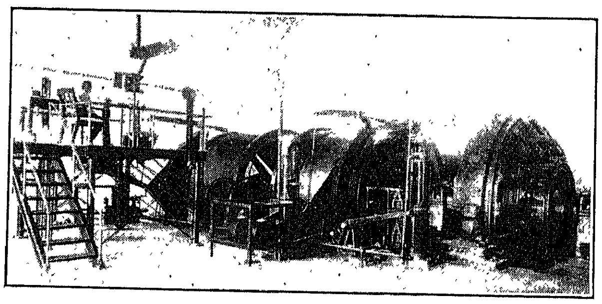

Fig. 7—3200-Hp., 79 Rev. Per Min. D-C. Hoist Motor

Largest Hoist Motor in Western Hemisphere. We are continually having our attention called to the ever increasing size of electrical equipment being used in the industries. One of the large electrical manufacturing companies is building for the Frood Mines of the International Nickel Company of Canada a 3200-hp., 79 rev. per min. d-c. hoist motor. On both the horsepower and torque rating, this motor is larger than any single mine hoist motor yet installed or selected for mine hoist applications in this hemisphere. Fig. 7 illustrates this motor.

Its armature will be 144 in. in diameter and power for the motor will be supplied by a fly-wheel motor-generator set consisting of a single a-c. motor driving two 1250-kw., 600-volt generators. The hoist has cylindrical drums 12 ft. in diameter and is of the balanced skip type for the handling of ore from a maximum depth of 3000 ft. The load will vary with the depth and at 2000 ft. the skip will handle 10 tons of ore at a speed of 3000 ft. per min.

This equipment will employ the variable voltage d-c. system of speed control.

Improved Equipment for Gaseous Mines. In gaseous coal mines an explosion of gas may occur, this explosion be communicated to the fine coal dust deposited on the sides, roof and bottom of the mines, thus extending and materially augmenting the initial explosion and, perchance, causing a disaster of large proportions. In order to prevent the gas explosion communicating with the coal dust, the latter is covered with rock dust which is distributed to the walls, roof, and bottom of the mine under air pressure. Fig. 8 shows a machine used for this purpose. The rock dust is contained in the hopper at one end of the machine and is distributed by the motor-driven blower. This equipment is capable of delivering the rock dust through several hundred feet of hose to entries on either side of the track. The blower delivers a constant volume of air at a fixed velocity regardless of the length of hose.

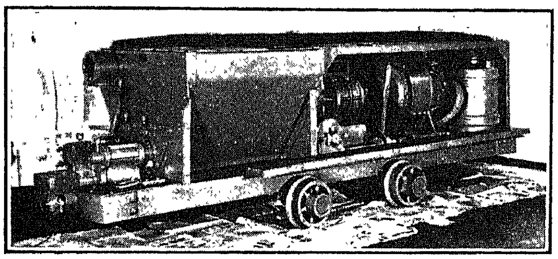

FIG. 8—MACHINE FOR DISTRIBUTING ROCK DUST

The electrical equipment is especially designed for use in gaseous mines and has been approved by the Bureau of Mines for this application. It consists of a 20-hp. permissible type motor and control. The motor has solid rear brackets and bronze screw type inspection covers on the commutator end. The controller is of the full magnetic push button type. The contactors, overload relay, starting resistor, and push button are all enclosed in a single case arranged for easy inspection of the equipment.

By using the packing gland type of lead entrance the electric cables can be run without external connection from the inside of the motor to the inside of the controller. The design results in a very simple method of mounting and wiring the electrical apparatus. The push buttons which are enclosed in the case are operated by two plungers extended through the case and protected by a housing cast integral with the top of the control.

The Largest Mine Locomotive. The largest single unit underground mine locomotive was exhibited at the American Mining Congress Convention in May. This locomotive weighs 38 tons and has the following limiting dimensions: Gage 35 in., height 46 in., width 64½ in., overall length 24 ft.-0 in. The locomotive is equipped with three 133-hp., 500-volt motors or a total of 399 hp. per locomotive. The motors are arranged for forced ventilation from a separate blower motor. The control is of the semi-magnetic type, series-parallel with overload relay and no-voltage protection.

The locomotive was designed for a haul of approximately four miles with an average grade of approximately 2.4 per cent and a maximum grade of 5.6 per cent for a thousand feet and will haul an average of 50 cars per trip and make 9 trips in 8 to 8½ hr. The car weight loaded is approximately 3½ tons average. Fig. 9 illustrates the locomotive.

Glass Industry

The application of motor drive in the glass industry is of course not new. The excessive demand of thin plate glass of the non-shattering type, and for ordinary thin plate, such as used in the auto and allied industries, has caused a general building and rebuilding program for this type of glass manufacturing.

The use of electrically driven mechanisms at practically every step and the fine instruments required as well as powerful cranes, etc., has created a great and growing demand for motors, controllers, and general equipment to improve the methods of manufacture of thin plate glass.

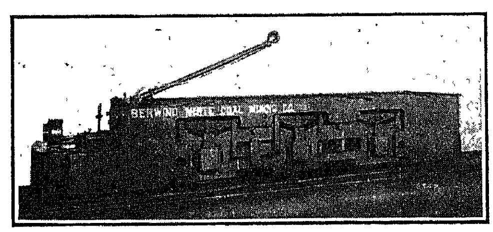

FIG. 9—LARGEST MINE LOCOMOTIVE

Electrical Refrigeration

The enormous growth of motor application in the field of electrical refrigeration is indicated by the fact that ten years ago this industry produced about 1200 units a year, whereas the year 1927 produced 1,500,000 units.

The introduction of the electrical refrigerator into the home has added during 1927 a revenue of $3,000,000 to the Power Companies' earnings.

An interesting application in this field is the use of single-phase motors mounted in rubber. All single-phase motors have an inherent double frequency torque

pulsation which gives rise to some noise and vibration. Fig. 10 shows a 1/30 hp. split-phase motor of the usual construction but with this unusual mounting.

The base of the mounting has vertical supports going up through the ventilating holes in the bottom of the end-flanges of the motor and offset around the shaft so that the top of the support is directly over the shaft and some distance above it. There are two holes in each support, one above and one below the shaft with rubber bushings in these holes. Two pins extending inward from the end-flange engage these rubber bushed holes and support the motor. The motor is thus supported entirely from these pins in the end-flange and there are no metal-to-metal contacts between the motor and its mounting. This rubber mounting has two advantages over a rigid mounting in that it eliminates a large part of the vibration normally transmitted to the apparatus on which the motor is mounted and it also reduces the usual motor noise to a minimum, as the motor can produce noise only by vibration in the relatively small surface of its own frame.

In this field also, it is interesting to note the application of what is essentially a two-phase motor from a

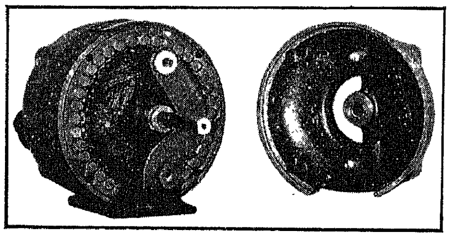

Fig. 10—Split-Phase Motor Frame with Cushion Base

single-phase line, one phase of the motor being connected directly across the source of supply and the other phase connected in parallel with the first phase through a capacitor. In order to secure best operation, it has been found desirable to make a change in connections on the capacitor as the motor comes up to speed. This change is made by the use of a single centrifugal device which operates a single-pole double-throw switch. Due to the fact that it has no commutator or brushes, it is extremely quiet and causes no radio interference except one slight click when the centrifugal switch operates. The fact that the motor operates as a polyphase motor has a tendency to eliminate the characteristic hum of a true single-phase motor.

Paper Mill Industry

A new application in the manufacture of paper is that of an adjustable speed motor to a paper winder. This drive consists of a direct connected variable speed motor and the necessary control equipment. The motor is designed to give a speed range of 4 to 1 by voltage control and to give a crawling speed for threading the paper by means of armature resistance. This particular drive was supplied at the mill of the Fraser Co., Ltd. at Madawaska, Maine, and has caused a great deal of favorable comment because it is an economical arrangement when viewed from the standpoint of first cost and has proved a very satisfactory arrangement from an operating standpoint, all the features having been combined in it which are ordinarily secured only through a Ward Leonard system of speed variation.

Electric Furnaces

For a number of years the wrought brass industry, concentrated in a comparatively few large plants, has used electric arc and induction furnaces almost exclusively for melting copper-zinc alloys. The cast brass industry, consisting of many small plants widely scattered, has been slower in the adoption of electric heat for melting but there was an increased use of electric furnaces for melting brass for castings. The brass industry as a whole uses comparatively small melting units, 75 to 200 kv-a., all single phase. There appears to be less objection than formerly on the part of public utility systems to single-phase loads of this character, and units as large as 300 kv-a. have been installed.

In the steel industry the use of the three-phase arc furnace of the three-electrode type followed the standard practise of the last two or three years and "electric steel" has now become a trademark to indicate a superior quality of steel.

There is a decided growth of interest in the possibilities of cast iron of uniform analysis and of definite physical properties. This is one of the most promising applications of the electric melting furnace.

The coreless type induction furnace, generally referred to as the "high-frequency furnace," entered the ferrous field for the production of high grade alloy steels. Completed equipment of this character included a 150-kv-a., 900-volt, 2000-cycle unit for melting steel, 1 60-kv-a., 900-volt, 960-cycle unit installed for laboratory service in a large steel plant, and a 187-kv-a., 900-volt, 800-cycle unit shipped to Sweden. All of these units consist of a motor-generator set, using a three-phase motor of standard frequency and voltage to drive a single-phase high-frequency generator, together with the corresponding high-frequency capacitor units.

In the December 16 number of the *Electrical Review*, London, there is an article on a high-frequency steel furnace, this furnace being operated by a 150-kw. motor-generator set and used for only the very finest steel. This appears to be another application of electricity which betters the product and does away with a great deal of hard exacting labor, inasmuch as it is the first radical departure from the primitive coke furnace for making crucible steel. This furnace is in operation at the Imperial Works of Messrs. Edgar Allen & Co., Sheffield, England.

Steel Mill Industry

Automatic Steel Mill. A great improvement in the rolling of steel was inaugurated during 1927 which has made it possible to roll the "H" shaped beam so desirable for columns in buildings. The improvement consists in using sets of rolls to roll simultaneously the flanges and web of the beam. The adjustments of all of the rolls is made automatically at the same time. Important new features were also developed for the motor driving these rolls.

Fig. 11 shows the main motor room for the new mills at the Homestead plant of the Carnegie Steel Company which roll these "H" section beams. The total capacity of the electrical equipment in this one room is nearly 85,000 hp., thus making it one of the largest industrial substations yet installed.

In the right center and extreme back part of the motor room are shown the reversing motors which drive the mill rolls of the roughing and intermediate 52-in. universal beam mills. Each of these mills has three pairs of rolls, all working simultaneously on various parts of the same beam section. The main horizontal

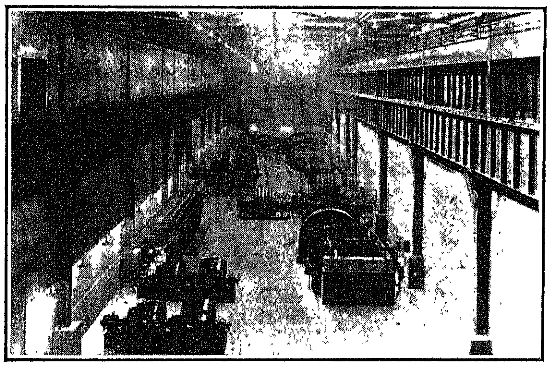

Fig. 11—Main Motor Room, Carnegie Steel Company

and vertical rolls are driven by a 7000-hp. motor, and the horizontal edging rolls are driven by a 200-hp. motor, both of these reversing motors being supplied with power from a 6000-kw. flywheel motor-generator set.

Automatic control is provided, which permits a single operator to control the operation of the two motors, the three screwdown motors, and the several table conveyor and transfer motors. By means of a plug-in board, the ratio of the speeds of the two reversing roll motors is predetermined and selected for each pass, and the screwdown setting of each set of rolls is selected for each pass. During operation, the operator then advances a multi-point master switch one position after each pass, and the control functions automatically to adjust the ratio of roll motor speeds and to set each of the sets of rolls, ready for the next pass.

By this method of control, the operation of the mill is very greatly simplified, the number of operators is reduced, and the product is of uniform quality due to the same processing of succeeding pieces.

Mill for Wide Flanged Beams. Another large equipment of unusual interest was placed in operation at the Lackawanna Plant of the Bethlehem Steel Company. The mill to which the motors were applied is used to produce wide flange beams. It consists of three units; a 54-in. reversing blooming mill, a 48-in. intermediate mill, and a 48-in. finishing mill. The blooming mill, which is one of the two largest reversing blooming mills in this country, is driven by a single-unit d-c. reversing motor rated 7000 hp., continuously at 50 deg. cent. rise and 40/80 rev. per min. This motor is capable of exerting a maximum torque of 2,400,000 lb. at one ft. radius. Direct current is supplied from a flywheel, motor-generator consisting of a 5000-hp., 375 rev. per min., 6600-volt induction motor, a 50-ton flywheel and two 3000 kw., 750 volt generators which are operated in parallel.

Another noteworthy application at the Lackawanna Plant of the Bethlehem Steel Company is the change of the layout of the rail mill which is now being made. The 44-in. reversing blooming mill will have a driving motor rated 7000 hp. continuously, 50 deg. rise and 50/120 rev. per min. Blooms from this mill will go to a 35-in. reversing roughing mill which will be driven by a d-c. motor rated 5000 hp. continuously at 50 deg. cent. and 50/120 rev. per min. Power for these two reversing motors will be obtained from a single flywheel motor-generator consisting of a 7000-hp., 375 rev. per min., 6600-volt induction motor, two 3000 kw., 375-rev. per min., 750-volt generators operating in parallel to supply power to the 7000-hp. blooming mill motor, two 2200 kw., 450-volt generators operating in series to supply power to the 5000-hp. roughing mill motor and a 75-ton flywheel.

Use of Synchronous Motors in Steel Mills. The increase in the use of synchronous motors for main roll drives in the past year is noteworthy. The new applications for the year include a 5000-hp., 40 deg., 1000-rev. per min., 2200-volt motor used to drive a 19-in. continuous sheet bar mill at the Kokomo Plant, Indiana, of the Continental Steel Corporation. A motor of the same horsepower rating but at 240 rev. per min. will be used to drive a 51-in. piercing mill installed by the Standard Seamless Tube Co. of Economy, Pa. Other motors are applied to copper and brass rolling mills.

Motor Rollers. The first applications of rollers of the type in which the driving motor is inside of the roller and made integral with it were made in the past year. These applications include motor rollers on four different parts of a continuous sheet mill at the plant of the American Sheet & Tin Plate Co., Gary, Indiana. These rollers are of different capacities and speeds, depending upon their location in the table and vary from 5 to 35 cycles per sec. They are operated through motor-generator sets consisting of alternators and adjustable speed d-c. motors to give the necessary speed variation over the different parts of the table.

Another application of these rollers is that at the Lorain Plant of the National Tube Co. Applications here include motor rollers on a runout table for conveying the rounds from the furnace to the piercing mill. Others are used to feed the pipes to and from the threading machines, this installation being entirely automatic, and still others for conveying the tubes through the oiling machines. All of the rollers for the National Tube Co. are made of a special form to accommodate the round stock.

There are many advantages in the use of motor rollers over the geared or coupled type of drive, chief of these being simplicity of mounting with resultant simplicity and cheapening of the table supports, and economy in space and power, and extreme flexibility of operation.

Oil Industry

Although electric power was slow to invade the field of oil production, rapid progress has been made during the last two years and now there are many fields using electrical power exclusively. A very good résumé of the operation of an electrically operated oil field is given in the *Electrical World* under date of February 4, 1928.

Application of Electricity to Pipe Line Pumping. Recently electric power has been used for pumping oil through pipe lines to replace the slow-speed plunger pumps driven by steam engines or occasionally a Diesel engine, on account of their very high first cost.

During the last two or three years pump manufacturers have made rapid strides in the design of centrifugal pumps suitable for this service and the engineers of the pipe line companies are beginning to realize the advantage of motor-driven centrifugal pumps for this work. Some of these advantages are low first cost, low maintenance, low attendance charges, quickness of installation, and reduced friction head due to steady even pressures. The low first cost (usually one-sixth to one-eighth of the steam station of the same capacity) is of considerable importance in selecting equipment, especially when the life of the field being served is of questionable duration and low fixed charges are prime factors in the total operating costs.

In the summer of 1927 the Illinois Pipe Line Company desired to increase the capacity of their main line across the State of Ohio, from 15,000 bbl. a day to 22,000 bbl. Rather than install additional pipe line capacity at great expense, this company put in booster stations using motor-driven centrifugal pumps at intermediate points between the steam stations. Ten five stage, 650-gal. per min., 1660-ft. head centrifugal pumps driven by 400-hp., 220-volts, three-phase, 60-cycles, 1800-rev. per min., synchronous motors with direct connected exciters were installed in five booster stations, two units per station. Only one pump is required to operate in each station, the second unit acting as a standby. See Figs. 12 and 13. Magnetic pushbutton starters of the auto-transformer type are used throughout, with pressure gages arranged to shut down the motors in case of low or excess pressures. The two pumps, motors, control and auxiliary equipment are mounted in a pump building 24 ft. by 34 ft. A fire wall is placed between the room containing the pump and the room containing the electrical equipment; the motor shaft passes through a stuffing box in the fire wall.

The sucess of these first installations has caused this company to purchase and install 27 additional

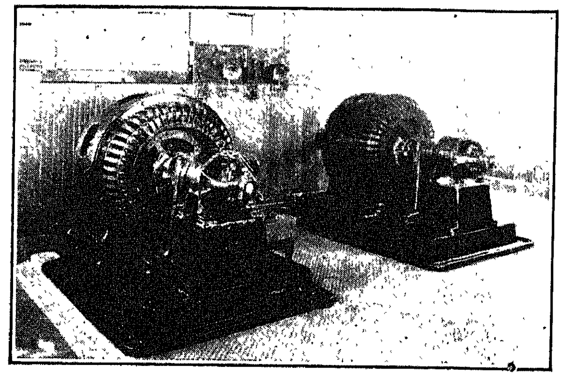

Fig. 12—Synchronous Motors in Booster Stations

units of the same kind to operate their new line running from Yates Pool to West Texas to Del Rio. Other companies have also realized the advantages of electric power for this service and have made similar installations so that this method of pumping is rapidly becoming the standard for pipe line service.

Electrical Welding

There was a marked advance in the application of electrical welding during the past year, both for the fabrication of electrical machines of all sizes and for the

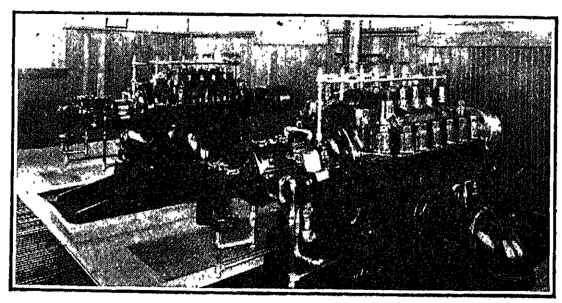

Fig. 13—Motor-Driven Centrifugal Pump

fabrication of structural beams and pieces necessary in the building industry.

The use of welded frames is rapidly becoming universal on account of the great saving in weight which can be accomplished by this method. Fig. 14 shows a welded frame for 100,000 kv-a. turbo generator and Fig. 15 shows a fabricated stator frame for one of the 40,000 kv-a. water-wheel generators for Conowingo.

First Arc Welded Railway Bridge. The first arc welded bridge of the through girder type is shown

by Fig. 16. This bridge spans Thompson's Run, having a span of 53 ft. 9 in. although the bridge is 62 ft. 4 in. over-all in length. There are 20 tons of steel in the structure and the main side girders each contain approximately 6 tons of steel. These girders are designed along rational lines in that the flanges are made from plate material and the web stiffeners are plate stock on edge,

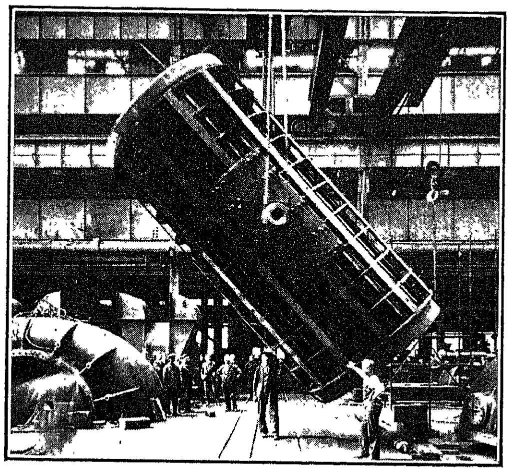

FIG. 14—100,000-KV-A. INNER STATOR FRAME WITH STACKED LAMINATIONS

no angles being used anywhere in the construction of the girders. The bridge is designed to handle a locomotive having a weight of 185,000 lb. on three sets of driving wheels.

The first arc welded railroad bridge of the through

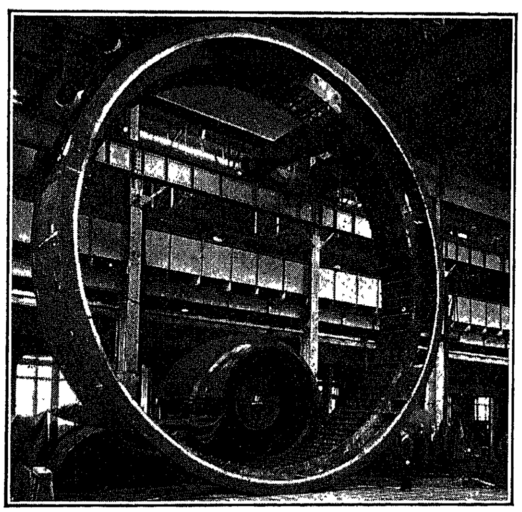

FIG. 15—GENERATOR FRAME

truss type is that shown by Fig. 17, which shows the bridge as completed before moving in position on the abuttments across the canal at the Chicopee Falls, Mass., plant of the Westinghouse Electric & Mfg. Co.

The plant shown in the background behind the bridge is that of the Fiske Rubber Co.

This bridge spans the power canal passing through Chicopee Falls, which is approximately 50 ft. wide. Owing to the layout of the railroad facilities, however, the bridge is required to cross the canal at an acute angle of 72 deg. As a result the trusses are approximately 135 ft. long and the over-all length of the bridge is approximately 175 ft.

The outstanding feature of interest in the design of the bridge is the fact that the welded design requires 80 tons of steel, whereas the riveted design, prepared by the railroad engineers, required 120 tons of steel. Also the connecting material in the case of the welded

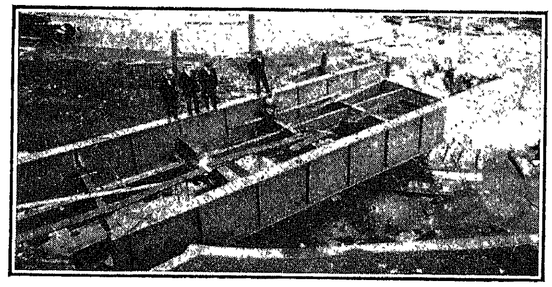

FIG. 16—ARC WELDED RAILWAY BRIDGE

bridge runs less than 5 per cent of the weight of the structure whereas in the case of the riveted design the weight of the connecting material is almost 30 per cent of the weight of the total structure.

Atomic-Hydrogen Arc Welding. Development work

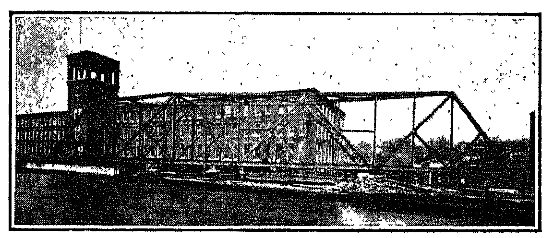

FIG. 17—COMPLETED ARC WELDED THROUGH TRUSS TYPE BRIDGE

on atomic-hydrogen arc welding was completed and a commercial equipment was produced for use on 60-cycle circuits.

With this method of arc welding, an alternating current is maintained between adjustable tungsten wire electrodes, Fig. 18, and hydrogen is fed to the arc around the electrodes. The hydrogen molecules are broken up into atoms by the intense heat and, in recombining outside of the arc and in contact with the work, heat is liberated far in excess of that obtainable by any gas flame alone. This heat is used to fuse the metals to be joined and, where additional metal is required, a filler rod may be fused into the work.

The hydrogen, being an active reducing agent, prevents the formation of oxides and hence produces a uniformly strong, ductile, and smooth weld. The metal being welded is not in the electric circuit and

need not be grounded or insulated. The arc, constantly maintained, but broadly adjustable in size and in intensity, lends itself to a wide range of work.

A transformer furnishes the required voltage, and the current at the arc is controlled by an automatic reactor. In this process, high voltage and low currents are required in the arc, which is the reverse of the conditions in ordinary arc welding. The arc is struck at 300 volts; but while welding, the arc voltage is varied from 90 volts for light work to 60 for heavier, and the current correspondingly varies from 20 to 70 amperes.

By this means, homogeneous ductile welds can be made on very thin metals or on some metals and alloys hitherto considered unweldable.

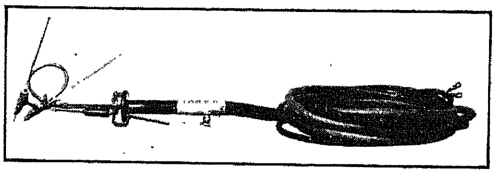

FIG. 18—ATOMIC HYDROGEN WELDING TORCH

Magnetically Controlled Arc Welding. It is claimed by one manufacturer that the superimposing of a strong magnetic field on the arc flame, permits the arc to travel through variable magnetic fields without disturbance. This magnetic control appears to give the arc a gyratory motion and the controlled arc has been called an "electronic-tornado," the magnetic field apparently giving a swirling or gyratory motion to the electrons in the arc. It is claimed that welds made by this new process are more uniform in structure and ductility than those of ordinary arc welding.

Heretofore metal deposited by electric arc welding has partaken of the characteristics of cast steel. By this new process the metal deposited in the weld shows equal or even better physical characteristics than the metal of the plates joined by welding. This is said to be a result of the purifying effect of the electronic tornado.

An article in the January issue of the *Welding Engineer* indicates that a metallurgist who examined micrographs of welds made by this magnetically controlled process states that actually the weld is heat treated steel, and for that reason is entirely free from undesirable hardness and that the refining effect of this new welding process produces weld metal fully as good as that which can be obtained in rolled steel of the same general purity.

CONTROL

Control has made many developments during the past several years and much was done during 1927. A great many individual devices could be cited indicating the improvements made. The following are given more or less to show the general trend of control. Generally, it should be pointed out that the evolution of dependable definite timing devices has limited the use of current limit and counter e. m. f. schemes of control. The general run of magnetic control is now of the definite time accelerating type.

The year 1927 saw a great deal of development and improvement in thermal overload relays for motor protection and protection for other machinery. The developments during the year are also noteworthy with respect to improvements in magnetic switches. Much has been learned with respect to the characteristics of different metals used as contact breaking and carrying points, also with respect to the advantages of multiple break per pole.

Automatic Pump Control. In the automatic control of a pump installation where the centrifugal pump is installed at a higher elevation than the sump, a vacuum pump is usually required for priming the centrifugal pump. The use of a pump valve to keep the pump filled with water so rarely gives satisfactory results in an automatic installation that this method of priming is not often recommended. The use of a sequence drum has made an improvement in automatic pump control. This sequence drum provides the automatic control to start the pump at high water level, stop the pump at low water level, and go through the priming process in starting. It repeats the priming cycle three times if necessary to prime the pump. If the pump is not primed after a third attempt, the sequence drum will lock out the control and a contact will be made on the drum energizing alarm circuit. In case the vacuum breaker switch remains closed, after the pump has primed, the main motor will not be disconnected from the line, but the sequence drum will stop on alarm contact, ringing alarm and lock out starting control, until repairs have been made. The sequence drum is, of course, motor-operated. See Fig. 19.

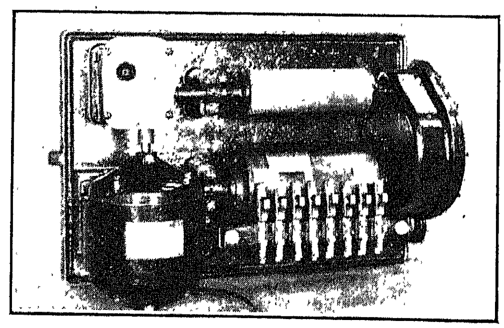

FIG. 19—MOTOR-OPERATED SEQUENCE DRUM

High-Pressure Valves. In connection with the motor operation of large valves in steam power plants and in the chemical industry, the trend is toward extremely high pressures, up to 3000 lb. per sq. in., and relatively high temperatures. This has imposed unusual requirements as to the positive and accurate seating of

the valves. Strains and resultant deformations may result from the pressures and from expansion and contraction of parts due to temperature changes. Also, dissimilar metals are used such as monel stems and chrome steel valve bodies, which have unlike temperature coefficients of expansion. Therefore the standard motor control with a mechanical limit set for an accurate number of turns of the yoke nut would, under certain conditions, not close the valve tight, or under other conditions it might seat the valve before this mechanical limit was reached and thus damage the valve seat.

To meet these conditions, a torque-limit valve control has been developed. This control assures the seating of the valve at a definite predetermined seating pressure, or a fixed torque of the motor.

The controller is provided with a mechanical limit which operates while the valve is still at an appreciable distance from the seat. When this limit operates a torque device relay is cut into circuit and as the valve approaches the seat, the seating pressure builds up, increasing the current passing through the motor until it reaches a predetermined value, at which time the motor is disconnected, properly seating the valve.

The control system allows full torque on the motor up to the actual tight seating point of the valve, and this type of control should be used for closing all Globe type of valves, and for gate type of valves on pressures exceeding 450 lb. per sq. in. and on temperatures of 500 deg. cent. and above.

High-Speed Printing Presses. The development of high-speed presses for printing newspapers and the tendency toward the use of a-c. power has produced new problems in the control and drive.

In operating newspaper presses a two-motor drive consisting of a small motor and a large motor, is generally used. The small motor operates through a gear train and overtraveling clutch, and is used to start, inch, and thread the paper through the press, at a speed of approximately 1200 papers per hr. The large motor which is connected direct to the press, drives it during the regular printing operation. The slowest speed required is for registering, which is at a speed of about 9000 papers per hr.

Newspaper presses operating at a maximum speed of 36,000 to 40,000 papers per hr., using 2, 3, and 4 press units of 16-page capacity each, are easily controlled and operated over the entire speed range either by d-c. adjustable speed motors or a-c. slip-ring motors, as the a-c. motors can be satisfactorily operated at a reduced speed equal to 25 per cent of normal, which is necessary to obtain the proper take-off speed. However, on high-speed presses operating at 60,000 papers per hr., the reduction in speed, without special provision, required on the a-c. slip-ring motor is so great that it results in breakage of the paper web during the transition period when the main driving motor takes the load from the starting motor.

To obtain satisfactory results on high-speed presses driven by a-c. slip-ring motors, a special control equipment has been developed. The objective is to obtain the same take-off speed for registering the web and to obtain the same pull on the paper web during the transition period, accelerating to the same printing speed as is obtained by means of regulating resistance in the secondary of the main motor on slower speed presses. To accomplish this a torque relay is used in connection with the equipment, which controls the torque of the press through a torque switch during the transition period. As the main motor accelerates, this torque relay controls the main motor and interrupts the acceleration when a certain speed and torque is reached. If, during the transition period, the speed falls below a certain point, this torque relay will again close the torque switch, tending to accelerate. The slight variation in speed obtained at this point is not perceptible and not objectionable from the printing standpoint.

The controller is operated from a push button station and when the web has been properly registered, the main motor can accelerate the press by manipulation of the push button station to the proper printing speed.

To date, a-c. control and drive equipments have been designed and operated on high-speed presses consisting of one and two 16-page units. Operating three or more presses together may involve some difficulties in collecting the paper webs.

Paper Machine Drives. A control system has been developed for giving remote control of the paper speed on sectional paper drives.

Sectional paper drives are generally operated by individual motors which are driven from a common generator and the speed is controlled by varying the voltage of the generator. In order to obtain stable speed the generator is provided with a voltage regulator.

In the past the voltage of the generator and the speed of the drive has been controlled manually at the motor-generator set, and the problem resolved itself into voltage control of the generator from a remote point and still keeping the generator under control of the voltage regulator at all times.

To obtain these results the voltage regulator operating by means of the torque produced in a moving electromagnetic system is used. Movement of this torque mechanism commutates the generator field current directly through regulating resistances. The torque system is connected directly across the voltage to be regulated and any voltage changes cause a displacement in the moving element because the torque produced in that element operates in opposition to an elastic recall system.

In order to compensate the regulator to cause it to regulate at a different voltage, it is only necessary to change the resistance in series with the torque coil. A motor operated rheostat which simultaneously commutates the generator field and the torque resis-

tance is used to effect the voltage change. Proper space resistance relations of the two circuits maintains the voltage regulator in operation at all times.

The voltage regulator and the motor operated rheostat is controlled by a push button located at the machine floor and the speed changes are accomplished without the attendance of an operator at the switch control.

Furnace Top Control. A variable cycle furnace top controller for use in connection with the McKee revolving top has been developed.

In the past it has been the practise to revolve the furnace top with the load deposited from the skip pocket before dumping into the big bell in accordance with a fixed cycle. Most commonly six loads have been dumped in succession at six different dumping points. With the newly developed controller, it is possible to vary the number of loads dumped into the different positions from four to nine. This change in cycle is being obtained by a manually operated position switch on the panel. This type of control insures better distribution in the material in the furnace as it is possible to vary the cycle depending upon the grade of material.

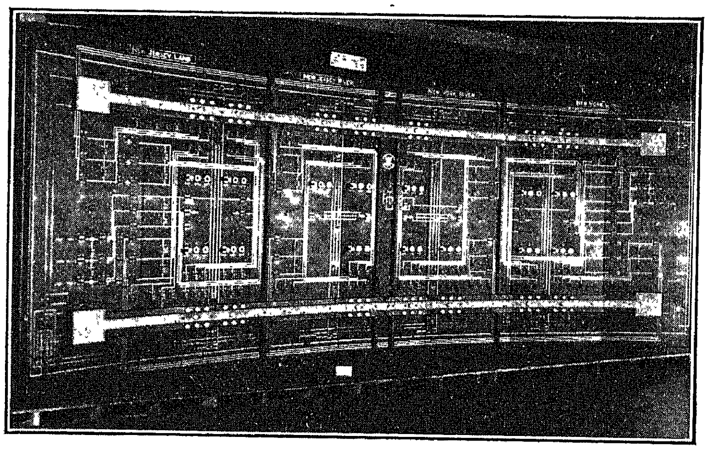

FIG. 20—SUPERVISORY CONTROL BOARD OF HOLLAND TUNNEL

Holland Tunnel Supervisory Control. The control equipment for the ventilation and operation of the Holland Tunnel connecting New York City with New Jersey has been designed to be handled by one man. This insures a maximum of safety with a minimum of operating force. The brains of this system is concentrated at the supervisory control board located on the top floor of the New York Administration Building. This board is built in the shape of an arc and composed of seven steel cabinets, as shown in Fig. 20, the cabinets being formed of sheets of ⅛-in. "stretcher-level" steel. At the rear and also within the cabinets are swinging steel doors, upon which are mounted the relays used on conjunction with the system.

The front of this board is a symbolic representation, both of a twin tube and the electrical circuit, including all feeders and motors. The board is divided by black vertical strips into five sections representing the four ventilation buildings and the mid-river sump. The names of the buildings are designated by name-plates shown near the top of the board. The two large trough-like castings running horizontally, one near the top and the other near the bottom of the control board, are symbolic of the north and south tubes respectively. The plateaus at the ends represent the plazas and the arrowheads indicate the directions of traffic.

Every oil circuit breaker control switch, motor speed switch, pump control switch, and their respective indicating lamps used in the tunnel equipment is duplicated on this board. By means of single direct-wire connections and the use of polarized type of relays, these various switches can control all the apparatus; likewise the lamps will indicate accordingly. The scheme of operation of this equipment is not at all like the standard supervisory control making use of the impulse method of using the automatic machine switching apparatus.

The control switches have a bar-like handle with the same finish as the miniature bus into which it is inserted. The position of this bar gives the operator a physical indication of the oil circuit breaker in addition to the indicating lamps. That is, when the control switch has been turned to close the breaker, the bar handle will be in line with the miniature bus. Likewise, when the switch has been turned to trip the oil circuit breaker, the handle of the switch will be left in a cross-wise position relative to the bus. When the control switch is turned to the closed position, its contacts impress a certain polarity over the single wire control to a receiving relay of the polarized type located in the ventilation building near the breaker. To trip same breaker the switch, when turned, will impress an opposite polarity on the receiving relay. The breaker lamp indication is brought back from the oil circuit breaker auxiliary switch to a receiving relay mounted on a swinging door in the rear of this control board; the same scheme of polarity that was used with the breaker control is employed also with the lamp indication.

At each breaker control switch, there is a green and white indicating lamp. The green lamp when illuminated, indicates that the breaker is closed. The white lamp has two degrees of brilliancy; the dim light indicates that the breaker has been tripped manually, while the bright light indicates that the breaker has been tripped automatically, due to some fault or failure.

The large lamp located on the raised part of the mimic tunnel, when illuminated, indicates what set of motors is feeding that particular section of the tunnel. The lamps on the upper raised section, above the trough indicates that the motors are being fed from the New York feeder, while the lamps on the lower raised station below the trough, indicates that the motors are being fed from the New Jersey feeder. Note that in order to insure continuity of service, each set of

motors, consisting of a blower and exhaust, can be fed from either a New York bus or a New Jersey bus.

The large indicating lamp located in the trough of the mimic tunnel is connected to the carbon-monoxide recorder equipment. The illumination of this lamp indicates that there is more than two parts of carbon monoxide in 10,000 parts of air in the exhaust ducts. The small red lamp located in line with the carbon-monoxide lamp, when brightly illuminated, indicates that particular point in the tunnel from which the fire alarm has been sent in. The lights along the edge of the troughs close to the raised section, indicate what lighting cabinet is feeding the tunnel at that particular point.

On account of the method of ventilation used, the fans can be run on three different speeds. Consequently, the engineers selected motors of the wound rotor induction type so that speeds could be obtained by varying the resistance of the rotor. The three switches, grouped together in a vertical center line above the three large indicating lamps on the mimic tunnel, are for speed control. To select a particular speed, the key or handle must be inserted in the corresponding switch. In order to prevent the operator from forgetting to select a speed when he starts up any one of the fans in that particular section, an alarm will be sounded until the speed has been designated. The speed equipment consists of contactors with dashpots and a timing relay enclosed in a metal cabinet located near each motor in the ventilation building. The electric supply for the speed control is taken from a small distribution transformer located in the same housing as the breaker, which controls the main power circuit to the particular motor. As the motors can be fed from either New York or New Jersey bus, the small distribution transformers will be automatically fed from the respective bus.

As shown on the mimic tunnel, three fans feed each section of the ducts. One group of speed control switches is supplied for each section so that if three fans should be operating at the same time in the one section, all will be revolving at the same speed. A white indicating lamp is mounted directly above each speed switch; the lamp being illuminated above the corresponding switch of the particular speed selected.

On the lower half of the left-hand end of the control board are shown the three incoming feeders from power houses located in New Jersey, each feeder being 13,200 volt, three-phase, 60 cycles. On the upper half of the right-hand end of the board are shown in a similar manner the three incoming feeders, having the same characteristics as those from New Jersey, from power houses located in New York. In line with the miniature bus for these feeders, are white indicating lamps which are known as bus potential pilot lamps. These lights have also two degrees of brilliancy, when dim indicate that the feeder is alive; when bright indicate that due to some abnormal condition, the feeder has been opened. The lamp extinguished indicates that the bus is dead.

The incoming lines feed three-winding, air-blast, power transformers, which have secondary voltages of 2300 and 440 volts, these potentials being required for the motors. All oil circuit breakers are of the truck type design. The 13,200-volt incoming lines, all tie breakers, and the 2300-volt motor breakers are of the standard design, while the 440-volt motor breakers, on account of their number, are built in two tiers in order to save space.

All the protective relays used on the incoming feeders and motor circuits are located in the various ventilation buildings near the respective motors. The incoming lines are protected against short circuit. The three-winding power transformers have differential protection. The motors are protected by thermal overload relays which take care of excessive temperature rise due to overload. This same relay has a short circuit element which will act instantaneously if a short circuit occurs. To protect the motor during the starting and stopping period against failure of the speed control devices, and for protection, should the dampers within the air ducts be closed while the motors are running, a long time-delay undervoltage relay has been supplied.

From the above description of the supervisory control system and its control board, the supervisory operator knows and sees exactly how every piece of apparatus composing this gigantic network is performing. He can tell whether the incoming line breaker is still feeding the equipment, or whether it has tripped out automatically; whether or not the designated fans are running properly at the selected speed; whether the percentage of poisonous gas is dangerous in any section of the tunnel; if a fire alarm has been sent in, and what section is affected. The level of the water in the various sump chambers can be determined by certain lamp indications. Should any change be made in the position of any particular apparatus, due to some fault or failure, a bell alarm will be sounded and a bright light will indicate the location and character of the trouble.

Miscellaneous Applications

Brick and Clay Industry. This industry is rather behind in the application of electrical power, the usual excuses being those of excessive dust, sulphur fumes, etc. These excuses are proved fallacious by installations in other industries. In one of the large Hudson River soft mud plants a complete electrified installation is now being built.

The superiority of electrical power over steam in clay plants is becoming universally acknowledged and practically all new plants are so equipped.

Ceramic Industry. Electrical energy is now recognized as an ideal fuel, particularly for ceramic manufacturers. It produces very clean heat, simplifies

furnace construction and produces the highest percentage of No. 1 ware.

Textile Industry. Electric heating was adopted for the first time to the cloth singeing machines which are used in the finishing rooms of textile mills. The singeing was previously done by gas or oil heat.

Most of the singeing machines in operation at present are of the horizontal type with burners or hot contact plates mounted in horizontal rows so that the cloth is in a horizontal position in its travel over them. By the adoption of electric heating units, it was possible to arrange them vertically over each other in two rows, so that the cloth would be in a vertical position when traveling over them.

This arrangement not only makes available the close control of the temperature which is characteristic of electric heating, but it also reduces the floor space required for the machine.

Bottle Making. The *Electrician* of November 4, 1927 describes a new machine put out by European manufacturers which makes over 5000 large bottles an hour and smaller ones at a higher rate. The machine is driven by a 15-hp. adjustable speed motor and is equipped throughout with roller or ball bearings.

Lighting. The application of an electric flashing system and a lantern of new design displaced kerosene buoy lights on the New York Barge Canal.

Artificial light has been further used in the horticultural field.

There has been a large increase in the application of lighting of special kind in the medical field where cures can be effected by the equivalent of sun rays.

Also in the medical field should be mentioned the application of cathode rays and their effects in the production of vitamines in yeast and other foods. This research has been aided by the development in 1927 of cathode ray tubes for operating potentials of 900,000 volts. In 1926 the maximum operating potential was 400,000 volts. The higher potential has increased the velocity and range of the cathode ray discharge.

Under lighting should be mentioned the enormous increase in applications of neon tubes for commercial advertising. Also the development of a new type quartz neon gas-filled lamp which resembles a ball of reddish orange fire and has great fog penetrating possibilities.

A unique application of lighting is towards the elimination of certain moths and insects.

Flood lighting has been applied to harvesting operations and to the lighting of athletic fields for night sports.

Synchronous Motors on Centrifugal Pumps. The use of synchronous motors on centrifugal pumps is increasing as is noted by the demand for 1800-rev. per min. and even 3600-rev. per min. synchronous motors for this purpose.

Oil Engine-Driven Alternators. A 3750 kv-a., 124-rev. per min., 60-cycle alternator for direct connection to a Busch-Sulzer oil engine is being erected by Tucson Gas, Electric Light & Power Co.

High-Voltage Transformers. Three 500-kv-a., 750,000-volt transformers have been installed by the Ohio Insulator Co. of Barberton, Ohio. In this installation, the three transformers are connected in series and are thus capable of developing 2,250,000 volts above ground. This is said to be considerably higher than that developed by any other transformers in the world.

Individual Wire Blocks. The application of individual d-c. drive for wire blocks has rapidly increased. Between 350 and 400 blocks have now been installed in such a drive. The principal advantages are the flexibility of the individual drive since the wire block may be operated at any speed desired for the particular work at hand; smooth easy start which can be secured with direct current and the consequent control advantages in starting the wire through the die; the safety features which may be introduced in d-c. motors and control.

Ward Leonard Control. It is very interesting to note the number of new applications that have been found for this old principle. By the use of Ward Leonard control combined with field weakening on the motor, speed ranges as great as 20 and even 30 to 1 can be secured. With such a Ward Leonard system the control is very inexpensive and goes quite a long way toward paying for the extra expense of an individual generator. This type of drive has been used on galvanizing take-up frames in several instances.

Tandem Drive for Strip Mill. Several continuous strip mills have been installed in the last year with individual motor drive in each of the mills where the material is in several mills at the same time but without any loops in the steel. This can be accomplished by d-c. motors if the motors are carefully tested and calibrated to operate together with special provision in the fields for keeping the motors in correct speed relations, without developing a loop or stretching the steel.

Anti-Friction Bearings. The use of ball and roller bearings in motor applications has increased at a rapid rate. Many companies use this type of bearing exclusively. One company reports good success with the use of tapered roller bearings and the extension of their use to vertical motors, both alternating current and direct current, with very satisfactory results. The thrust capacity of the tapered roller bearing makes it ideal for many applications.

Totally Enclosed Fan-Cooled Motors. The totally enclosed, fan-cooled motor fills a demand for a moderately priced machine to successfully operate in the presence of dust or gas that has a deteriorating effect on insulation. These are generally of two types, those with external fans at both ends of the motor, which take in the outside cooling air at both ends and blow it

towards the center, and those with fans at one end only, the cooling air being either drawn or blown across the motor from end to end. There is a constantly increasing demand for these fan-cooled enclosed motors and conditions indicate a considerably greater production this coming year.

Texrope Drive. This is a comparatively new development and was mentioned in a previous report of this committee. It is interesting to note that repeated tests show a transmission efficiency of 99 per cent for recommended maximum load. The large coefficient of friction allows the transmission of full power with a small tension on the loose side of the drive and successful operation with minimum bearing pressures.

Mining Work

ANNUAL REPORT OF THE COMMITTEE ON APPLICATION TO MINING WORK*

To the Board of Directors:

In reviewing recent progress made in the application of electrical power in mines, one is inclined to conclude that it has been effected by the general economic conditions prevailing in the mining industry. Overproduction facilities in men and mines, labor problems, and freight rates are factors which are vitally influencing the prosperity and accomplishments of the business.

Conferences of mine managers and manufacturers of mining equipment, together with the meetings of engineering societies, indicate that the mechanization of mines is making great progress; in fact, definite conclusions have been reached that, under many conditions, mechanization pays. Considering the great investment required, and the new problems arising in the concentration of men, equipment, and supplies, creditable economies are being effected in the mechanical loading of coal where but an average tonnage is obtained from the equipment. Mine managers are realizing that the successful loading of coal is not solved by the purchase and installation of the machine, but that it involves many other operations, such as mining the coal, car dispatching, transportation, and mine planning. The question of cleaning the coal must also be included, since machine-loaded coal contains the impurities which, in hand loading, are left in the mine.

In 1926, about ten million tons of bituminous coal were loaded mechanically by 455 machines, this being an increase of approximately 60 per cent over 1925. While no complete reports are available at the present time concerning the number of machines in operation during 1927, certain information indicates that there will be a decided increase over those used in 1926. Due to the suspension of mining in Illinois and Indiana, the tonnage loaded in 1927 will not show much increase.

As the mechanization of mines continues, so does also the demand for equipment approved by the United States Bureau of Mines. This is due to the fact that much of the equipment required in mechanical loading and conveying machinery is used at the face workings where the maximum danger from gas and dust exists. The use of electrical equipment approved by the Bureau of Mines is becoming so general that there is in operation a bituminous coal mine with a daily output of 3500 tons, in which all of the underground electrical apparatus carries the permissible plate of the Bureau. Power for the motors in the mine is supplied by storage battery power trucks.

In some mines, mechanical loading means the use of several 125-hp. scraper hoist motors. A loading system of this type requires the transmission of power at 2200 volts. Proper protection is attained when using electricity at the above voltage, by the use of metallic armored cables placed in intake airways, and supported by a steel messenger wire. A cable crossing a track is taken underneath it in a conduit or concrete duct. Branch line taps are safeguarded with the usual protected oil switches.

The maintaining of a satisfactory d-c. voltage at the working face becomes more important each year. A 200-kw. portable rotary converter with its necessary accessories has been profitably used to attain such results. The transformers, switchboard, and control panels are mounted on trucks with the same gage as the mine tracks. A special frame structure is bolted to the converter making it possible to attach a truck to it. A movement of the entire station is contemplated every six months. Experience has shown that a complete move requires a period of eight hours.

An improved electric cap lamp consisting of a two-filament gas filled bulb and a bakelite head piece has been placed on the market. The new bulb produces more light, and the head piece, being an insulator, reduces the possibility of accident when worn in the vicinity of electrical conductors. When the main filament burns out, the auxiliary filament may be turned on, thereby enabling the miner to complete his day's work or come out of the mine. As the intensity of illumination in the mines is increased, greater safety may be expected, and no doubt an improvement in the efficiency of labor will follow.

Comprehensive dispatching systems are being placed in operation, their success depending upon a more general use of telephonic and automatic signal systems. In large mines, a system of this type is necessary to get the highest operating efficiency from the haulage system. Telephones are used to distribute the cars, and a signal system moves the trains over the main haulage roads. These systems relieve the mine foremen of considerable detail work, and give them more time for other important mine management problems.

The haulage costs in mines with a large output are being reduced by the introduction of larger mine cars and heavier locomotives. Main line locomotives equipped with three axles and weighing 35 tons are now being used in mines where two-axle locomotives were too small for economical operation. Locomotives of this type have an electropneumatic control, air brakes, and dynamic braking for handling loads on down grades.

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*APPLICATIONS TO MINING WORK:

W. H Lesser, Chairman.

F. N. Bosson,	A. B. Kiser,	W. F. Schwedes,
Graham Bright,	Carl Lee,	E. D. Stewart,
M. M. Fowler,	John A. Malady,	F. L. Stone,
E. J. Gealy,	C. H. Matthews,	W. A. Thomas,
L. C. Ilsley,	F. C. Nicholson,	E. B. Wagner,
G. M. Kennedy,	H. F. Pigg,	J. F. Wiggert,
R. L. Kingsland,	L. L. Quigley,	C. D. Woodward.
	Herbert S. Sands,	

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

An increase in the motor capacity of large locomotives is being obtained by the use of forced ventilation, which is produced by a separate motor-driven blower mounted on the locomotive. The ventilation of the motors has been found to double their continuous rating. Notwithstanding the additional equipment necessary for ventilating the motors, the results obtained are so satisfactory that it has been adopted as standard practise by some manufacturers building three motor locomotives weighing 25 to 35 tons.

The largest mine locomotive ever built has been recently placed in service. It weighs 38 tons, has a 36-in. gage, and semi-elliptic leaf type springs with a three point equalization. Three 133-hp., 500-volt d-c. motors with forced ventilation will furnish the power. A semi-magnetic control arranged for series parallel operation of the motors in either direction constitutes the control equipment. The drawbar pull on level track at 33⅓ per cent adhesion will be 23,333 lb. at a speed of 7.4 mi. per hour.

Mechanical loading has concentrated and increased the service required from gathering locomotives to such an extent that heavier and slower speed locomotives are proving to be the best type. A reduction in the speed of gathering locomotives to 3½ mi. per hour makes it possible to do the same work with a consumption of 30 to 40 per cent less power.

The transportation of coal long distances by belt conveyors instead of locomotives is making progress. Mines in which the coal travels from the face to the tipple on conveyors are possibilities.

The world's largest electrically operated shovel will go into operation during this year in the open-pit mines of Illinois. It is equipped with a 15-cu. yd. dipper, and a boom 120 ft. long. Two 450-hp. motors will provide the power for hoisting, and two 150-hp. motors will do the swinging. A Ward Leonard control will be used, involving a motor generator set, the synchronous motor of which will have a capacity of 1700-kv-a. Shovels of this size will reduce the unit cost of the material handled, and make it possible to increase the ratio of overburden to coal in strip mining.

Where gaseous mines are being supplied with electrical power from large public utility plants over long transmission lines, installations are being made which will make it possible to operate the fans, and to hoist the men during periods when the normal supply of power has failed. An installation of this type consists of two fans, and a man hoist driven by a-c. motors, three-phase, 60 cycles, and 2200 volts. When an interruption of the power occurs, the above equipment is supplied with power at 40 cycles, and 1500 volts. Under these conditions, the control apparatus will function properly, and the motors will operate at two-thirds speed, which is sufficient to keep the mine clear from gas and to hoist the men. The emergency power is produced by a gasoline-engine-driven, 200-kv-a. generator capable of being started by a push-button in case of a power interruption.

A notable electrification program of a large copper mining company has just been completed. The complete electrification of its 28 mines with a connected motor load of about 65,000 hp. shows that electrical power is an important factor in the copper industry. Engineers have overcome many difficulties in the installation and maintenance of electrical apparatus in copper mines, where the action of copper sulphate is so harmful.

In another open-pit copper property, there are 23 electrically-operated shovels in service. This year the entire steam haulage system consisting of 52 steam locomotives will be replaced by 37 trolley locomotives each weighing 75 tons.

In hard rock ore mines, as distinguished from coal mines and other soft ore mines, experiments are being conducted on the electrical equipment required by loaders, slushers, and other machinery. Much progress is being made in the adaptation of motors to this exceptionally severe service.

Automatic controls for mine substations, fans, pumping plants, and air compressors are being continually developed and placed in operation. At the present time there are about 200 automatic pumping stations in operation in the anthracite coal field, representing an annual saving in labor cost of approximately $500,000. The automatic stopping and starting of air compressors has been developed and several are in successful operation.

A rather unique application of electricity in the mining industry consists in using it for heating the bathing water for those employees who work on holidays or during periods when most of the regular force is idle. In one instance, a steam plant is necessary to heat the water for the normal force of 600 men, while during idle days, immersion heating units in a tank provide sufficient hot water for the reduced force of 25 men.

It is becoming more noticeable each year that the managers of the mines are giving more attention to the maintenance and care of the electrical equipment, resulting in a decreased maintenance cost and a better operating efficiency. The mine electrician in charge of the electrical equipment is given more authority and is directed by the electrical engineer in all technical questions. Frequent inspections of the mine by the engineer and the electrician, together with a good operating organization materially reduce the number of equipment failures, so disastrous to good production.

Marine Work

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO MARINE WORK*

To the Board of Directors:

The activities of the Committee on Applications to Marine Work this year were devoted chiefly to the dissemination of the Marine Standards (A. I. E. E. Standard No. 45), cooperation with the N. F. P. A. (Committee on Fire Detection and Alarm), cooperation with the American Marine Standards Committee on specifications for water tight receptacles, and the expenditure of further efforts to induce the U. S. Steamboat Inspection Service to recognize and properly classify the electrical engineer on shipboard.

A. I. E. E. Standards No. 45 were issued in June 1927. The committee this year made a special effort to distribute the Standards to all departments of the marine industry likely to be interested and as a result of this campaign 750 copies were sold.

The Standards are recognized and accepted by the various marine classification and insurance societies, naval architects and marine engineers, and are incorporated as one of the regulating provisions in their specifications. A. I. E. E. Standards No. 45 are therefore a recognized success and will serve to standardize the electrical installations on shipboard and to stimulate the use and proper care of electrical machinery in the marine field.

The Conference Committee on Fire Detection and Alarm requested our cooperation in connection with recommendations which it was preparing for the Steamboat Inspection Service, of fire alarm and fire detecting systems. In compliance with this request, our committee reviewed its proposed recommendations in detail and subsequently held a joint meeting with its representatives, at which all points of difference were discussed.

The committee also cooperated with the special committee on water tight receptacles appointed by the American Marine Standards Committee of the Bureau of Simplified Practise, to draw up specifications for water tight receptacles for shipboard service.

Considerable time was spent in connection with the proposition of inducing the U. S. Steamboat Inspection Service to make provision in its regulations for the proper rating and classification of the electrical engineer on shipboard. To this end, our committee prepared its report containing a statement of the status of the present electrical personnel, reasons for higher and proper rating and recognition of the electrical engineer on board ship, together with a suggested list of ratings and grades for the electrical personnel of the various classes of ships. These recommendations were made in such manner as to permit licenses in the different electrical grades being taken out by those of the present steam and Diesel classified engineers who qualified.

This report was presented by our subcommittee on personnel at the annual meeting of the U. S. Steamboat Inspection Service in Washington in January. Although final action was deferred by the Steamboat Inspection Service at its annual meeting, it decided to take our recommendation under consideration in the regular routine of its body and prepared plans to circularize the marine operators for the purpose of soliciting their opinions in the matter of classifying electrical personnel. It is felt that favorable action will be taken by the Steamboat Inspection Service and its regulations modified in the course of time. Our subcommittee on personnel is keeping in close touch with the situation.

In addition to the above chief items considered by the committee this year, the question of revision of present specifications was taken under advisement and arrangements made to keep the specifications up to date automatically by considering and acting upon all proposed changes as they are presented. In this way the time and effort required to get out the revised issue when necessary will be considerably minimized.

The outstanding electrical developments in the marine field during the past year are as follows:

1. The construction of five 3000-ship hp. turbine-electric drive U. S. Coast Guard Cutters.
2. The placing in service of the S. S. *California*, an 18,000-ship hp. twin-screw turbine-electric drive passenger ship for the Panama Pacific Steamship Line. A sister ship to the *California* is now under construction.
3. The conversion by the U. S. Shipping Board of three of their largest cargo vessels (*Courageous, Defiance*, and *Triumph*) to Diesel electric drive. These vessels will have machinery suitable for 4000-ship hp. normal and 4500-ship hp. maximum continuous.

Besides the above chief developments there has been a number of smaller craft equipped with electric propulsion. The application of electrical equipment to ships is continuing at an increasing rate and the future looks hopeful indeed.

With the passage of the Jones-White bill and its approval by the President, the American Merchant Marine has received its first real encouragement since the World War period. This bill contains several provisions which will undoubtedly stimulate the American marine industry. We can anticipate rapid developments in which electricity will play a very important role.

*APPLICATIONS TO MARINE WORK:
W. E. Thau, Chairman,
R. A. Beekman, Vice-Chairman.
J. L. Wilson, Secretary,

Edgar C. Alger,	J. S. Jones,	Wm. H. Reed,
H. C. Coleman,	A. Kennedy, Jr.,	Edgar P. Slack,
E. M. Glasgow,	J. B. Lunsford,	H. M. Southgate,
H. Franklin Harvey, Jr.,	E. B. Merriam,	C. P. Turner,
Wm. Hetherington, Jr.,	I. H. Osborne,	Oscar A. Wilde,
H. L. Hibbard,	G. A. Pierce,	R. L. Witham.

Presented at the Annual Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Electric Transportation

ANNUAL REPORT OF COMMITTEE ON TRANSPORTATION*

To the Board of Directors:

The application of electricity to transportation proceeded during 1927 at a healthy rate, and new developments in apparatus and equipment continued, several interesting applications being introduced during the year.

STEAM RAILROAD ELECTRIFICATION

Although no new electrification projects of major importance were completed during the year of 1927, two extensions were opened which had as their particular aim the further simplification of electric operation already existing, *viz.*, the Bay Ridge extension of the Long Island Railroad permits electrically-operated freight trains from the New York, New Haven & Hartford Railroad to pass over the Hell Gate Bridge Route to the tidewater freight terminal at Bay Ridge, Long Island; the Chicago, Milwaukee, St. Paul & Pacific Railroad has electrified its passenger terminal in Seattle, Washington, together with its line from Black River Junction over which trains had previously been handled by steam power.

Of the incompleted projects: the Pennsylvania Railroad will place in service shortly its suburban electrification from Broad Street Station, Philadelphia, to Wilmington, Del. and West Chester, Pa. The Great Northern Railway is proceeding with the extension of electric operation from Cascade Tunnel to Wenatchee, Washington. The New York Central Railroad is electrifying its west side freight yards in New York City. The New York, Westchester & Boston Railway is continuing its line to Port Chester, N. Y. The Detroit, Toledo & Ironton Railroad is working on the extension of its existing electrification from Flat Rock on to Petersburg, Mich.

The principal new project getting under way at the present time is the electrification of the suburban lines of the Reading Company around Philadelphia, Pa. It has been announced also that the Boston, Revere Beach & Lynn Railroad is planning to electrify its line.

Of electrifications placed in service during the year of 1926, one of the most interesting, the Chicago Terminal electrification of the Illinois Central Railroad, reports a marked increase in traffic and revenue for the first year of operation.[1]

Long Island Railroad. The Bay Ridge extension of the Long Island Railroad has been electrified with the 11,000 volt overhead catenary, single-phase, 25-cycle system for freight operation. This line joins the Bay Ridge freight terminal of the Long Island Railroad with the New York Connecting Railroad's Hell Gate Bridge Route to the New York, New Haven and Hartford Railroad at Port Morris, N. Y. The route is 20 miles in length.

Power is transmitted over a 22,000-volt, three-wire system with 11,000 volts between trolley and ground, and is received from the New Haven Railroad distribution system; in emergency it can be obtained from one 5000-kw. variable ratio frequency changer at the Long Island's East New York substation. This frequency changer is normally used as a synchronous condenser for power factor correction. No. 4/0 copper feeder wires are connected to the trolleys through auto-transformers at six balancer substations, four of which are on the Long Island and two on the New York Connecting Railroad.

The catenary system is non-ferrous with a single 4/0 bronze contact wire, copper auxiliary wire and high-strength bronze messenger wire. Inclined catenary is used in general on curves. The supports consist largely of rolled structural "H" beams. Rails are bonded with two No. 1 copper, 37-strand flame-welded bonds per joint.

The seven double-unit, gear-drive locomotives built for switching service have a wheel arrangement of 0-6-0 + 0-6-0, and weigh 158 tons each. The six motors on each complete locomotive are rated at 235 volts and operate with forced ventilation. The maximum starting tractive effort is 100,000 lb. and can be obtained up to 7½ mi. per hour. The maximum operating speed is 25 mi. per hour. Through traffic is handled by New Haven locomotives.

In addition to the Bay Ridge a-c. electrification, the Long Island Railroad is adding to its d-c. operation to the extent of 75 mi. of freight tracks and sidings, which will allow electric operation of all freight service within the electrified portion of the railroad. The work is 50 per cent completed and is to be completed by October 1st, 1928. A special "T" section third-rail of high conductivity is being used for all sidings and yard tracks.

Chicago, Milwaukee, St. Paul & Pacific Railroad. The western terminal of the Chicago, Milwaukee, St. Paul & Pacific are Seattle and Tacoma, Washington. Electric service ran into Tacoma, and service to Seattle had been handled by steam from Black River Junction. During the year of 1927, the line, 10 mi. of double track from the junction into Seattle, was electrified. Power is furnished from the earlier electrification through the overhead distribution system, and no new substations were constructed. This electrification is 3000-volt,

*COMMITTEE ON TRANSPORTATION:

J. V. B. Duer, Chairman.

Reinier Beeuwkes,	John Murphy,	N. W. Storer,
E. R. Hill,	W. S. Murray,	H. M. Vandersluis,
W. K. Howe,	W. B. Potter,	Richard H. Wheeler,
D. C. Jackson,		Sidney Withington.

1. *First Year of Electric Operation in Chicago*, by W. M. Vandersluis, A. I. E. E. QUARTERLY TRANS., Vol. 47, 1928, No. 1, p. 217.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

d-c., with an overhead catenary system having a double contact wire.

Pennsylvania Railroad. The Pennsylvania Railroad is completing the electrification of its suburban service from Philadelphia, Pa., to Wilmington, Del., on its main line to Washington, and to West Chester, Pa., on the Wawa Branch. This project was outlined in last year's report. Overhead catenary is used, energized with 11,000-volt, 25-cycle, single-phase current.

Great Northern Railway. The project of the Great Northern Railway to electrify its line between Wenatchee and Skykomish, Wash., is proceeding rapidly. Grade and curvature realinements are being made, and the new Cascade Tunnel from Berne to Scenic, (7.79 mi. long) is more than 65 per cent completed. Electric operation, which now extends from Skykomish through the old Cascade Tunnel, is to be extended through the new tunnel and on to Wenatchee before the end of 1928. The project will operate on 11,000-volt, single-phase, 25-cycle power, using motor generator locomotives with d-c. traction motors.

Orders have been placed for locomotives similar to those which are now in operation; that is, two additional type 2–6 + 6–2 and two additional type 2–8–2 + 2–8–2 locomotives, having continuous ratings of 3000 hp. and 3660 hp. respectively.

New York Central Railroad. The New York Central Railroad is proceeding with the electrification of its west side yards in New York City. The overhead trolley system at 600 volts d-c. is to be used as far down town as 60th Street. Below this the motive power will be self-contained power units.

New York, Westchester & Boston Railway. The New York, Westchester & Boston Railway is completing the extension of its Port Chester, N. Y., line as far as Rye, N. Y. Multiple unit suburban service is operated on 11,000-volt, 25-cycle, single-phase power.

Detroit, Toledo & Ironton Railway. The Detroit, Toledo & Ironton Railway is proceeding with the electrification of 26 mi. of line from Flat Rock to Petersburg, Mich. This will be an extension of the existing 11,000-volt, 25-cycle, single-phase electrified line described in last year's report, which runs from Fordson to Flat Rock, Mich.

Reading Company. The Reading Company is planning extensive improvements in its Philadelphia facilities, and expects to electrify 85 mi. of track with a 11,000-volt, 25-cycle, single-phase system.

Power will be furnished to this electrification over 22,000-volt feeders by a three-wire system with 11,000 volts between the overhead catenary and ground. The eventual program calls for transmission between substations at 66,000 volts.

The initial project comprises multiple unit service from the Reading Terminal in Philadelphia to Chestnut Hill, to Lansdale on the Bethlehem Branch and to Hatboro.

Boston, Revere Beach & Lynn Railroad. The Boston, Revere Beach & Lynn Railroad, a narrow gage line running out of Boston, Mass., plans to electrify a route of 15 mi. It is proposed to use a 600-volt overhead catenary system for multiple unit operation.

City and Suburban Railways

On electric street railways increased acceleration is being obtained by the use of light weight cars and more powerful motors with the latest design of control, thus tending to relieve congestion on city streets.

Trial installations of the new type of drive mentioned in last year's report have been put in service in a number of instances. This is the automotive type propeller-shaft drive by which unsprung weight is greatly reduced, with a corresponding reduction in noise and maintenance. Improved installations have been made in reduction gear drive with entirely spring-suspended motors having a flexible driving joint.

Marine Propulsion

The largest turbine-electric passenger ship, *California,* was launched October 1st, 1927. The displacement is 30,250 tons. Power is supplied to the propellers by two synchronous induction type motors each with a maximum continuous rating of 8500 ship hp. at 120 rev. per min.

The installation of Diesel-electric drive has been extended during the year to include three new lightships for the Department of Commerce as well as coast guard cutters, large double-ended ferry boats, a packet boat, and cargo boats.

Bus Transportation

Gas-electric drive for motor buses and motor coaches is increasingly popular. Experiments have been made on electric transmission for taxicabs.

Recent Developments

Diesel Electric Locomotives. The past year brought forth a novel arrangement of the Diesel engine prime mover with electric drive:

In electrification of its west side yards in New York City the New York Central Railroad has decided to use an overhead contact wire within the city limits only as far down town as 60th Street. Below this point it is desirable to employ a self-propelled unit. The locomotive chosen for this service, therefore, operates on third rail or trolley at 600 volts d-c., or can be propelled by power from a self-contained 300-hp. Diesel engine-driven generator, augmented for peak requirements by a storage battery. When load requirement is for less than 300 hp. the current from this battery is replaced by the generator.

Gasoline-Electric Rail Cars. During the year of 1927, approximately 150 gasoline-electric motor rail cars were ordered by the railroads of the United States. One 300 hp. oil-electric car was placed in service.

Trolley-Storage Battery Locomotive. Two electric locomotives furnished with power from a storage battery and also from an overhead trolley wire are in

service for yard switching service on the Chicago, North Shore & Milwaukee Railroad. When the locomotive is receiving current from the trolley the battery is charged by a motor-generator set.

High-Speed A-c. Circuit Breakers. Although oil circuit breakers with rapid operating characteristics have been available for several years in a-c. switching, one of the most interesting developments of the past year has been the construction of an air circuit breaker for operating on 11,000-volt a-c. circuits and having speed characteristics similar to d-c. installations This type, as well as oil circuit breakers operating on the same principle, is to be used by the Pennsylvania Railroad on its extension of electrified suburban service around Philadelphia.

Overhead Catenary. The construction of overhead catenary on the Great Northern Railway electrification from Skykomish to Wenatchee, Wash., is an application of the formula proposed by O. M. Jorstad[2] for inclined catenary.

Supervisory Control. All four transformer substations on the Philadelphia to West Chester electrification of the Pennsylvania Railroad are to be controlled from the Wawa signal tower by supervisory control. The synchronous visual type is being installed.

Another interesting installation of supervisory control is the West Hempstead substation of the Long Island Railroad, now under construction, at which three 1000-kw. mercury arc rectifiers are controlled from Mineola substation two miles away. The rectifiers can be started by the supervisory system in approximately 20 sec.

Train Communication. Radio communication between locomotive and caboose and between train and station has been the subject of considerable experiment. An installation of this type is in service on the New York Central Railroad.

Mercury Arc Rectifiers. The use of the mercury arc rectifiers in electric railway substations is still limited to a few installations. A summary of the operating experience of one railroad with this equipment is contained in a paper entitled *Operation and Performance of Mercury Arc Rectifiers on the Chicago, North Shore & Milwaukee Railroad Company.* This paper was presented by Caesar Antoniono at the Regional Meeting[3] in Chicago, Ill., November 28-30, 1927.

TECHNICAL PAPERS

The committee has obtained for presentation at the 1928 Summer Convention a group of interesting papers. They are as follows:

High-Speed Circuit Breakers, by J. W. McNairy, General Electric Company.

The High-Speed Circuit Breaker in Service on the Illinois Central Railroad, by W. P. Monroe and R. M. Allen, Illinois Central Railroad.

Arrangement of Feeders and Equipment for Electrified Railways, by R. B. Morton, Gibbs & Hill, New York, N. Y.

Operating Experience with High-Speed Oil Circuit Breakers, by B. F. Bardo, New York, New Haven & Hartford Railroad.

High-Speed Circuit Breakers for Railway Electrification Work, by H. M. Wilcox, Westinghouse Elec. & Mfg. Co.

Protection of Electric Locomotives and Cars to Operate with High-Speed Circuit Breakers, by E. H. Brown, Pennsylvania Railroad Co.

2. *Standardized Catenary Design,* by O. M. Jorstad, A. I. E. E. TRANS., Vol. 46, 1927, p. 1125.

3. A. I. E. E. QUARTERLY TRANS., Vol. 47, 1928, No. 1, p. 228.

Electric Welding

ANNUAL REPORT OF THE COMMITTEE ON ELECTRIC WELDING*

To the Board of Directors:

During the past year, marked progress has been made in the application of electric welding to an increasing number of industrial uses including welding of pipe, pipe lines, structures, and cracking stills for gasoline production. A few outstanding applications are mentioned by way of example in the following paragraphs.

One of the largest welding jobs completed during the year was the Mokelumne River Project, a pipe line supplying water to Oakland and other Bay Cities near San Francisco. This line is 90 mi. long. The pipe is 66 in. in diameter and its thickness varies from ⅜ in. to ⅝ in. depending on the water pressure in the particular section of pipe. This job is completed and is, so far as known, the largest single job of welding which has ever been undertaken.

This pipe was so large that it was necessary to join two plates in order to get the required diameter, one joint being made on each side of the pipe. These were welded by the automatic carbon-arc welding process. After each section of the pipe was welded, it was tested by hydraulic pressure at a fiber stress of about 23,000 lb. per sq. in., and while under this pressure, heavy sledges were dropped from a 4-ft. height on each side of the joint, the sledges being one foot apart. This gave a shock test to the joint at the time when it was subjected to the maximum hydraulic pressure.

The contract price on this job of arc welding was twelve million dollars. The best figure offered for the same pipe riveted was fifteen million dollars.

During the year, 45 mi. of 7-in. oil pipe line was electrically arc welded in Louisiana. The pipe was made in the ordinary way and the ends of the pipe were welded. The chief advantage of this method is that the finished pipe line is free from the leakage that sometimes occurs at joints made by threaded couplings in the old way.

This pipe was welded at $1.25 per joint contract price. According to the people who did the welding, the actual cost was 58 cents per joint. The best proposition for welding this pipe by any other method than the metallic arc was $2.75 per joint.

During the year, a number of cracking stills for the production of gasoline from crude oil were welded by the A. O. Smith Corporation. They have been put into service for carrying pressure as high as 1000 lb. to the square inch and a temperature as high as 900 deg. fahr. This is work which can be done only by the welding process. The results cannot be accomplished at all by the older riveting process.

Four papers on electric arc welding were presented at the Winter Convention of the Institute. One of these papers by J. B. Green[1] of the Fusion Welding Corporation dealt with the influence of the covering of the electrode on the characteristics of the arc. During its presentation slow-motion pictures of the arc taken with infra-red light were shown. These disclosed how the metal goes across the arc from the electrode to the work.

The paper by P. Alexander[2] of the Research Department of the General Electric Company at Lynn, Mass., dealt with the influence of the surrounding atmosphere on the arc.

The paper by A. M. Candy[3] of the Westinghouse Electric & Manufacturing Company described a five-story building recently erected by welding, and a paper by A. P. Wood[4] of the General Electric Company described what is being done at Schenectady in the way of welding electric machines of all descriptions.

Since that time, a bridge has been erected by welding by the Westinghouse Company at their plant at Chicopee Falls. This bridge has 80 tons of structural steel in its construction and would have required 120 tons if it had been erected by the riveting method in the regular way.

Early in 1928 three prizes offered by the Lincoln Electric Company for the best papers on electric arc welding through the American Society of Mechanical Engineers were awarded by a committee of seven judges representing the Engineering Societies and the Bureau of Standards.

The first prize of $10,000 was awarded to J. W. Owens of the Newport News Shipbuilding & Dry Dock Company, for a paper on "Electric Arc Welding in Ship Construction."

The second prize of $5000 was awarded to Professor H. Dustin of Brussels, Belgium, for a paper covering the method of calculating the strength of welding, giving data not heretofore available.

The third prize of $2500 was awarded to H. E. Rossell of the Philadelphia Navy Yard on the use of electric arc welding in the construction of bulkheads.

The American Welding Society has had committees on structural-steel welding and on pressure-vessel welding at work during the year and substantial progress has been made in the work of the committees, although no final report has been issued.

J. C. LINCOLN, *Chairman.*

*COMMITTEE ON ELECTRIC WELDING:
J. C. Lincoln, Chairman.

C. A. Adams,	Alex. Churchward,	Ernest Lunn,
P. P. Alexander,	O. H. Eschholz,	J. W. Owens,
C. W. Bates,	F. M. Farmer,	William Spraragen,
Ernest Bauer,	H. M. Hobart,	H. W. Tobey,
A. M. Candy,	C. J. Holslag,	Ernest Wanamaker.
	C. L. Ipsen,	

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

1. A. I. E. E. Quarterly TRANS., No. 2, Vol. 47, 1928, p. 820.
2. Ibid., p. 706.
3. Ibid., p. 711.
4. Ibid., p. 717.

Iron and Steel

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO IRON AND STEEL*

To the Board of Directors:

Your committee is pleased to present the following statement covering the progress of development in applications in the Iron and Steel Industry during the year ending July 31, 1928.

Constantly during this period the iron and steel industry has added to its general electrical equipment. These general additions have been towards modernizing of existing installations quite as much as anything, and all effort is directed steadily towards reduction in production costs by addition of improved machinery.

The tendency to increase blast furnace equipment is not present and this may be said to be true generally of the fundamental processes of smelting iron ore, in coverting iron into steel or in rolling the steel into the primary shapes. Such electrical additions as have been made in the foregoing are in the nature of changes of older equipment to modern.

The principal interest during the current term has been in the finished product mills which we shall term the secondary mills.

Predominant in this regard are installations in strip mills and in cold rolling, these electrical installations being modern and recording definite advance in the production of hot strip steel and in cold rolled strip.

Close regulation of the mill drive is required and to give this, motors and control have been developed and installed. Micrometric adjustment of the rolls has been obtained through motors and control specially designed for the purpose. The reeling of the strip steel has been accomplished automatically by mechanical tools, electrically driven and controlled. This accomplishment marks a definite advance in the production of perfect strip steel.

Steady improvement in detail of motors and control for such service is shown in the apparatus installed, and this is marked rather than any positively new product of our industry.

Throughout the term your committee has kept in touch with the proceedings and personnel of the Association of Iron and Steel Electrical Engineers. It has been our purpose to help the Association as we may and its proceedings again are referred to the Institute as the most complete record available of developments electrically in the Iron and Steel Industry.

In conclusion, your committee commends the plan of keeping continually in touch with the Association of Iron and Steel Electrical Engineers, giving it service wherever possible and bringing to the Institute its reports and findings, with suitable recognition. Your committee just concluding its services takes this means of acknowledging and expressing its appreciation of the assistance rendered by these reports for the current term, as well as by the constant contact with representatives of the Association.

A. G. PIERCE, *Chairman.*

*APPLICATIONS TO IRON AND STEEL PRODUCTION:

A. G. Pierce, Chairman,

A. C. Bunker,	S. L. Henderson,	F. O. Schnure,
F. B. Crosby,	O. Needham,	J. W. Speer,
A. C. Cummings,	A. G. Place,	G. E. Stoltz,
M. M. Fowler,		T. S. Towle,

High-Speed Circuit Breakers

J. W. McNAIRY*
Associate, A. I. E. E.

Synopsis.—High-speed circuit breakers have been successfully applied to d-c. railway systems for a number of years, but designs suitable for application on 12,000-volt single-phase systems have not been available until recently.

A description of an air circuit breaker design suitable for 12,000-volt applications and having a speed of operation comparable with the d-c. type has been included.

The method of applying the magnetic type of mechanism previously used for d-c. breakers to the a-c. type breaker has been described. The theory of the operation of the saturated transformer type of trip circuit used for this purpose has been given.

Typical oscillograms of short circuit tests showing the high speed of operation on a-c. circuits are included.

The method of obtaining selective operation in connection with railway feeder circuits has also been outlined.

The use of this type of breaker on a 12,000-volt single-phase system makes possible the same degree of protection and selective operation as is now being realized on d-c. systems.

I. Introduction

HIGH-SPEED circuit breakers were first applied on d-c. railway systems for the protection of commutating apparatus against the effects of short circuits or flashover. Later development led to their application to all of the power circuits of this type of system. A paper describing the principal features of a complete breaker installation of this type on the d-c. terminal electrification of the Illinois Central R. R., Chicago, was presented at the June 20, 1926 meeting of the A. I. E. E.† Reference was made at that time to the development work being carried on in connection with a-c. applications.

The higher voltages of the trolley network of the usual a-c. system make high speed operation of circuit breakers more difficult and progress has, therefore, not been as rapid as with the d-c. type. Some applications to railway feeders of a-c. breakers designed to operate considerably faster than the usual oil breaker, have been made in the past, but speeds approaching that of the d-c. breaker have only recently been attained.

Both oil and air break types having a speed of operation comparable with the d-c. type have recently been developed and commercial designs suitable for a-c. voltages up to 12,000 volts are now available.

The application of an air circuit breaker to this type of service marks the first application of breakers of the air type to moderately high a-c. voltages.

II. Advantages of High-Speed Operation on A-C. Railway Circuits

Short circuits are necessarily more frequent on railway systems than on other types of power distribution networks, because of the nature of the service. High-speed operation of the protecting breakers for single-phase a-c. systems reduces the effects of short circuit stresses on transformer and generator windings and limits burning of insulators, conductors, or parts of motive equipment from arcs resulting from these short circuits, in the same manner as on d-c. applications. Breakers of this type are frequently effective in preventing the burning off of trolley wires in case of an insulator, arc-over thereby minimizing delays in service from this source.

One of the most important problems in connection with a-c. railway electrifications is that of inductive interference with adjacent communication and signal circuits under short circuit conditions. The low impedance of the grounded track return circuit results in a maximum current in case of failures of the trolley circuit, and the ground current is, therefore, usually limited only by the impedance of these metallic conductors. The railway circuit differs in this respect from the usual power circuits where there is no ground metallic return circuit. Induced voltages in adjacent low voltage circuits are therefore, on the average, higher and appear more frequently than in regions where ordinary power distribution networks are located.

It is expected that the application of high speed breakers to the a-c. railway system will greatly reduce this interference by reducing to a minimum the duration of induced voltages in the parallel circuits. The reduction in the duration of the induced voltage minimizes the duty on protective devices in the communication circuits and it is expected that the false operation of relays, bells, and other devices, resulting from this induced voltage will be eliminated to a great extent. This is, perhaps, one of the greatest benefits to be derived from the application of this type of circuit breaker to the a-c. railway feeder.

III. Speed of Operation

The total time required for the operation of the usual a-c. circuit breaker may be divided as follows: 1, time required for relay operation, 2, time required for the separation of contacts, and 3, time required for extinguishing the arc.

In some forms of breakers, particularly those the subject of this paper, the relays have been eliminated, the circuit breaker being operated directly by the short circuit current.

The speed of operation of the mechanism is more or

*Railway Equipment Engg. Dept., General Electric Co., Erie, Pa.

†A. I. E. E. Trans., Vol. XLV, 1926, p. 962.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

less definitely fixed by the mechanics of the device and separation of the contacts occurs at a definite time after the trip point is exceeded.

For a-c. applications, the preferred breaker is one which opens the circuit at the normal zero point of the current wave, thereby avoiding undesirable voltage transients. Since separation of the contacts may occur at any instantaneous current value depending upon the magnitude of the short circuit current and the displacement of this current wave, the arc extinguishing system should be so proportioned that the current will not be forced down too rapidly before a normal zero point is reached.

This is usually not difficult since at zero current no energy is delivered to the arc and it is most easily extinguished at this point. It is possible, however, to design high speed breakers having too powerful a blowout or current rupturing system so that when the first short circuit current loop approaches a cycle in duration, and the contacts open when the line current is near the peak of the wave, the circuit may be opened too rapidly and undesirable transient voltages may result.

It is sometimes assumed that most failures on a single-phase 12,000-volt system occur at the peak of the voltage wave and, therefore, the usual short circuit is symmetrical with a duration of a normal half cycle for the first current loop. A great many short circuits, however, are produced mechanically, the conductors coming together so that the short circuit is established at any point on the voltage wave. Records obtained during experimental investigations using contacts in both air and oil for applying short circuits at 12,000 volts show transients having all degrees of displacement of the current wave.

The duration of the first loop of current is, therefore, frequently less than one-half of a normal cycle. The magnitude of the current of such a first loop is not a fair indication of the severity of the short circuit and the breaker does not receive full tripping current or current through the blow-out system until after the second current loop is reached.

The design of a breaker to limit all short circuits to a single loop of current, therefore, is difficult and if successful, the relatively powerful current rupturing system might reduce the current at a dangerous rate when the first loop approaches a cycle in duration.

It therefore appears that the most logical design of an a-c. breaker is one capable of opening heavy short circuits at the first zero after a current loop having a duration of one-half a normal cycle or longer.

IV. Oil vs. Air Type Breakers

One method of obtaining high speed operation is greatly to increase the mechanical speed of the conventional type of oil breaker so that sufficient arc length is obtained in the specified time for the interruption. This means the exertion of relatively great operating forces either by powerful springs or solenoids with a corresponding increase in the mechanical difficulties in starting or stopping the mechanism.

One of the most effective means of rapidly increasing the arc length is by means of the magnetic blow-out. By properly directing the forces exerted on an arc stream drawn between contacts of a circuit breaker by the fields of the blow-out coils, the arc can be lengthened at almost any desired rate. The contacts of the breaker therefore need only be separated sufficiently to stand the voltage as the circuit is opened by the collapse of the arc stream. By applying the magnetic blow-out to an oil breaker, the necessary contact separation at the instant the circuit is interrupted can be greatly reduced and a mechanism moving at moderate speeds can be utilized.

The speed of operation and rupturing capacity of experimental switches of this type have met expectations.

Elimination of oil, however, is always desirable where possible. This is particularly true for railway applications.

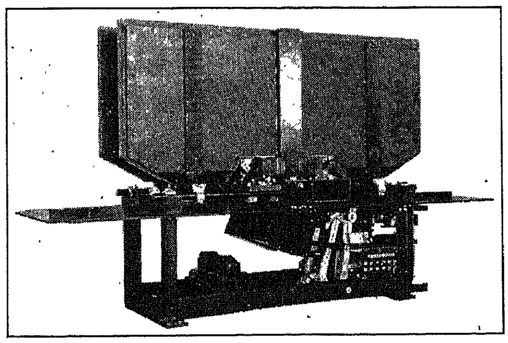

Fig. 1—12,000-Volt, 1500-Ampere A-c. Air High-Speed Circuit Breaker without Out-door Housing

The feeder network of important sections of electrified railway systems where continuity of power supply is imperative, requires a relatively large number of breakers for proper sectionalizing. On four-track systems of this type, the 12,000-volt breakers may average as high as two per mile and the maintenance of such a large number is obviously an important item in the operating expense.

Exposure of current carrying conductors of the railway network to the wear and tear of current collectors, in addition to conditions common to all aerial conductors results in frequent short circuits. The majority of these failures are to ground, which in railway circuits means a line to line short, the current being limited by circuit reactance only. Railway circuit breakers are therefore frequently called upon to open heavy short circuits.

The effect of repeated interruptions on oil circuit breakers is well known. If a given circuit breaker is called upon to open a circuit repeatedly without attention, the oil deteriorates to such an extent as to endanger

the reliability of the breaker. Repeated short circuits are most likely to occur during bad weather conditions when filtration or changing of the oil is most difficult, particularly in outdoor installations. The air breaker is therefore much to be preferred for this type of service,

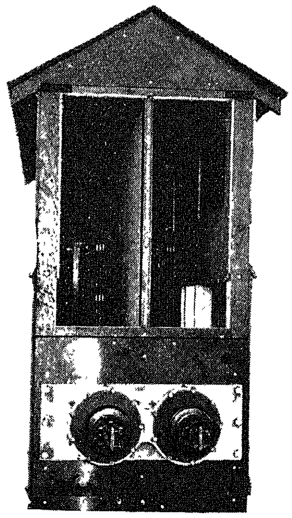

FIG. 2A—HIGH-SPEED AIR CIRCUIT BREAKER IN OUT-DOOR HOUSE WITH ONE END REMOVED TO SHOW LOCATION OF CIRCUIT BREAKER. ALSO SHOWS LOCATION OF HIGH-VOLTAGE TERMINALS

assuming that it is the equivalent of the oil breaker in all other respects.

The d-c. air break circuit breaker has demonstrated its ability to withstand repeated short circuits without deterioration or objectionable damage to contacts. A-c. air break breakers of the same general type have,

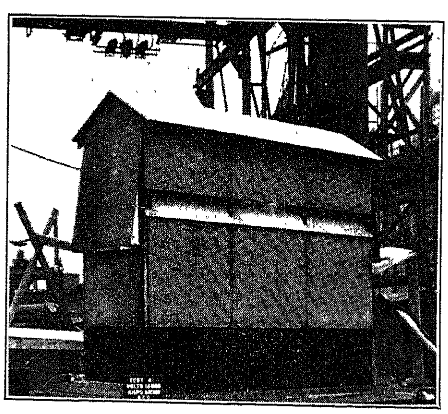

FIG. 2B—12,000-VOLT, 1500-AMPERE HIGH-SPEED AIR CIRCUIT BREAKER COMPLETE WITH OUT-DOOR PROTECTIVE HOUSING OPENING 24,000 AMPERES AT 14,000 VOLTS. OSCILLOGRAM OF TEST SHOWN ON FIG. 6

during experimental investigations, withstood 20 or more maximum short circuits repeated at two minute intervals without requiring attention or without deterioration of the current rupturing ability, and are on a par with the d-c. type in this respect.

On the other hand there is this to be said against the air circuit breaker:

1. The air breaker proper is not suitable for outdoor mounting and a protective housing is necessary. An air breaker complete with self-contained housing suitable for outdoor installations, is shown on Fig. 2. Fig. 2B was taken by leaving the photographic plate exposed while the breaker was opening a 24,000-ampere, 12,000-volt short circuit, the oscillogram of which is shown in Fig. 6.
2. The operation of the circuit breaker on heavy short circuits makes somewhat more noise than the oil type.
3. The application of the air breaker is at present limited to the moderately high a-c. voltages.

Both types of breakers will, therefore, undoubtedly find a field of application on a-c. railway feeder circuits.

V. MAGNETIC OPERATING MECHANISM

Practically all d-c. high speed breakers are of the magnetic tripping type, most designs making use of a

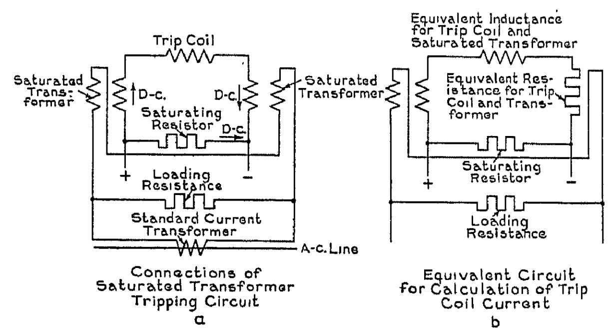

FIG. 3—CONNECTIONS OF THE TRIPPING CIRCUIT FOR THE MAGNETIC TYPE OF A-C. HIGH-SPEED CIRCUIT BREAKER

flux shifting principle, where the flux is shifted from a holding armature to a magnetic by-pass circuit to release the breaker. The principle of operation of the flux shifting type is well known and has been described repeatedly in publications.* Briefly, it consists of a holding magnet energized by a d-c. coil across the poles of which a holding armature is bridged. Between the poles a tripping coil is introduced in such a way that when a current of proper polarity is applied the flux is shifted instantaneously from the armature to the core of the tripping coil, thereby releasing the breaker. This type of mechanism, when tripped under short circuit conditions by the line current, provides practically instantaneous release by eliminating tripping relays, a very effective arrangement when maximum speed is desired. This mechanism has been successfully applied to both oil and air type 12,000-volt a-c. breakers.

Some means of providing a unidirectional current in

*Tritle, U. S. Reissue Patent 15,441.

"New Type of High Speed Circuit Breaker," by J. F. Tritle, *G. E. Review*, Vol. XXIII, p. 286.

the tripping coil of this type of mechanism is essential for applications on a-c. circuits. The saturated current transformer type of trip circuit was adopted for this purpose, Fig. 3. The tripping circuit is usually designed for current of 5 amperes so that standard current transformers can be used in the main power circuit.

The operation of this trip circuit perhaps may be better understood by first considering the phenomena responsible for the so-called "starting current" when voltage of proper polarity is suddenly applied to a transformer, the core of which is magnetized by residual flux. The "starting current" for the transformer is the result of lowered reactance because of over-saturation of the core, the available range in flux in one direction having been reduced because of the initial residual flux.

The transformers used in the tripping circuit are of normal current transformer design. When there is no alternating current through the windings, the flux in the cores of these transformers is maintained near the

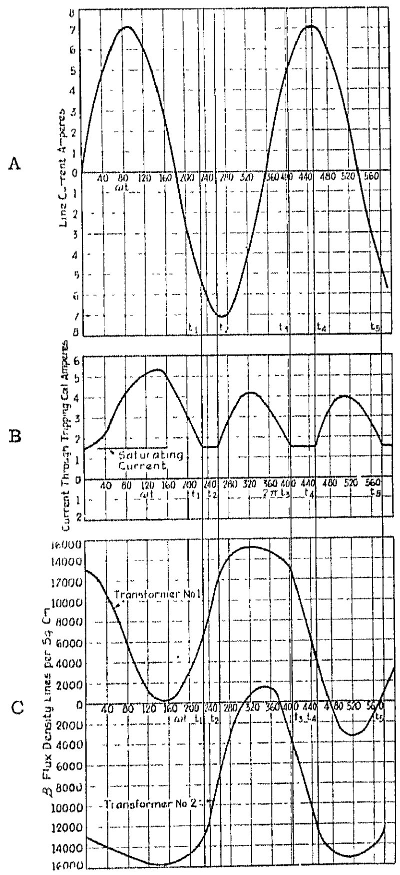

Fig. 4—Calculated Current and Flux Curves for Saturated Tripping Transformers used in Connection with the Magnetic Type of Mechanism of the A-c. High-Speed Circuit Breakers

saturation point by direct current through one of the windings of each transformer, this current being the same as that used for the holding coil of the circuit breaker.

The connections are such that when current of given direction is passed through the primary winding of both transformers, such as during the first half cycle of an a-c. short circuit, it exerts a m. m. f. to increase the flux in the core of one transformer and decrease the flux of the other transformer simultaneously.

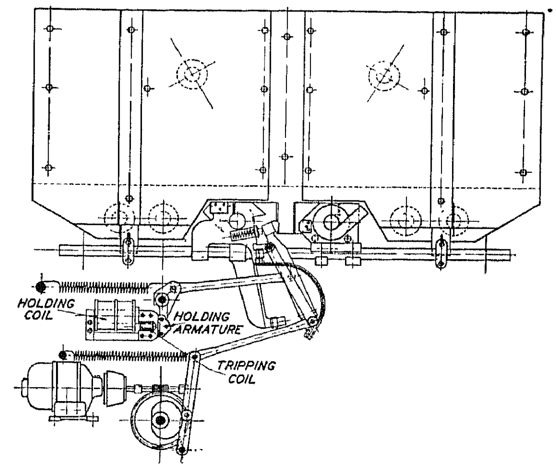

Fig. 5—Operating Mechanism of the Air Break 12,000-Volt A-c. High-Speed Circuit Breaker

Since the cores of both transformers are initially saturated in opposite directions, the decreasing flux in one transformer generates a secondary voltage whereas the transformer in which the flux is increasing generates only a slight secondary voltage because of saturation in the core. The secondary voltages of the two transformers are connected in opposition around the tripping coil circuit and the resultant unbalanced voltage circulates current around the circuit formed by the trip coil, transformers, and resistors as shown by the current curve of Fig. 4b.

No matter what the direction of the primary current, one transformer will be active on the first half cycle, the polarities being such that the current impulse through the trip coil is always in the same direction. The phenomenon is transient and the unidirectional current is not maintained under steady state conditions.

This arrangement does not provide a steady overload trip point so that standard types of overcurrent relays are usually provided for this purpose. The high speed trip functions only in case of short circuit or heavy overload which results in a suddenly increasing line current.

Any of the usual types of relay protective systems may be used in conjunction with the high speed trip.

In an endeavor to provide a more complete explanation of the operation of these saturated transformers, the following analysis is offered:

The performance of the transformers is affected by magnetic hysteresis in the iron core. The following analysis is intended mainly as an indication of the factors affecting the performance of these transformers and hysteresis effects have therefore been ignored for the sake of simplicity. The following assumptions were also made for the same reason.

1. The transformer which is active for a given direction of primary current is assumed to hold its ratio from the instant the flux is started down, that is, the exciting current is assumed to be negligible.

2. The inductance of the transformer which is inactive because of saturation has been assumed to be constant above the saturation value. The current through both the primary and secondary windings of the inactive transformer acts to increase the saturation.

3. It is assumed that the transformer which is inactive on the preceding half cycle becomes immediately active as soon as the total current through the windings is reduced to the d-c. saturation value.

The expression for the line current in case of an a-c. short circuit is

$$I = I_M \sin(\omega t - \gamma) + I_M \sin \gamma \, \epsilon^{-\frac{t}{T}} \qquad (1)$$

where

I_M = peak of sustained current wave, through secondary of line current transformer, t = time

γ = time phase angle of the starting moment

ϵ = 2.718

The following symbols are employed.

L_1 = total inductance of trip coil circuit (saturated transformers and tripping coil)

R_1 = total resistance of trip coil circuit

L_2 = total inductance of loading circuit, Fig. 3

R_2 = total resistance of loading circuit, Fig. 3

I = total current in secondary of line current transformer

i_1 = current through trip coil

i_2 = current through loading circuit

ω = $2 \pi f$

t = time in seconds

T = time constant of main power circuit.

The equivalent circuit for the period during which a current impulse is passing through the tripping coil is shown by Fig. 3B.

The current through the tripping coil of the circuit breaker is determined as follows:

One to one ratio; saturated transformers are considered. The fundamental differential equation for the circuit is

$$R_1 i_1 + L_1 \frac{d i_1}{d t} = R_2 i_2 + L_2 \frac{d i_2}{d t} \qquad (2)$$

also

$$I = i_1 + i_2 \qquad (3)$$

$$\frac{d I}{d t} = \frac{d i_1}{d t} + \frac{d i_2}{d t} \qquad (4)$$

substituting (1) in (2) and eliminating i_2 terms

$$(R_1 + R_2)\, i_1 + (L_1 + L_2) \frac{d i_1}{d t} = I_m \Big[R_2 \sin(\omega t - \gamma) + R_2 \sin \gamma \, e^{-\frac{t}{T}} + L_2 \, \omega \cos(\omega t - \gamma) + \frac{L_2}{T} \sin \gamma \, e^{-\frac{t}{T}} \Big] \qquad (5)$$

which is integrated for i_1

$$i_1 = I_M \Bigg[\left(\frac{R_2 (R_1 + R_2) + \omega^2 L_2 (L_1 + L_2)}{(R_1 + R_2)^2 + (L_1 + L_2)^2 \, \omega^2} \right) \sin(\omega t - \gamma) + \left(\frac{\omega L_2 (R_1 + R_2) - R_2 \, \omega (L_1 + L_2)}{(R_1 + R_2) + (L_1 + L_2)^2 \, \omega^2} \right) \cos(\omega t - \gamma) + \left(\frac{(R_2 T + L_2) \sin \gamma}{T (R_1 + R_2) - (L_1 + L_2)} \right) e^{-\frac{t}{T}} + C e^{-\left(\frac{R_1 + R_2}{L_1 + L_2}\right) t} \Bigg] \qquad (6)$$

The above relation holds only during the period when one transformer is active and the other inactive.

The magnetic trip circuit is sufficiently responsive to trip on instantaneous current values, the armature being released if the current through the trip coil exceeds the setting during the peak of an a-c. wave. The breaker is therefore released on the first current impulse which exceeds the trip point and the determination of the first tripping impulse is most important in connection with breaker performance.

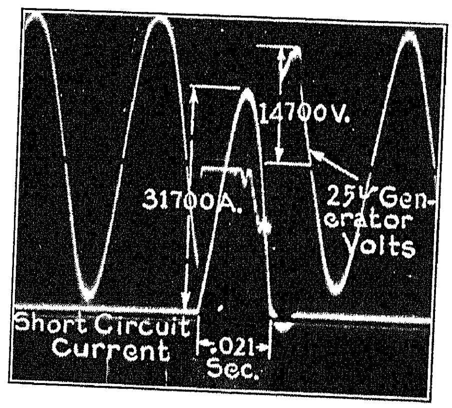

FIG. 6—OSCILLOGRAM OF "OCO" SHORT CIRCUIT TEST AT 14,000 VOLTS, 24,000 AMPERES, R. M. S. ON 12,000-VOLT AIR CIRCUIT BREAKER

The current through the trip coil of the circuit breaker for a symmetrical short circuit namely with $\gamma = 0$ has been calculated for a typical case using equation (6) as follows:

The constants of the circuits involved are as follows:

L_1 = 0.11 henrys
L_2 = 0
R_1 = 5.6 ohms
R_2 = 12.0 ohms
T = 0.00625
I_M = 7.1 amperes

Referring to Fig. 3a the resistance of the saturating resistor is made the same as the total resistance of tripping coil and transformer secondary windings and the steady direct current supplied to this circuit for saturating the transformers divides equally between the two parallel paths.

The resultant d-c. voltage drop produced by this

current in the parallel paths is equal and opposite around the circuit through which the tripping current circulates and therefore does not enter into the determination of the tripping current with the exception that the current value obtained from equation (6) is superimposed on the d-c. saturating current as shown by Fig. 4b.

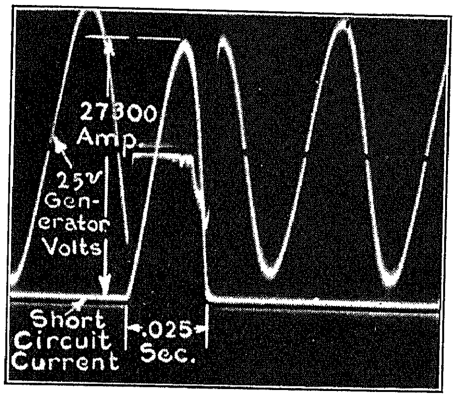

FIG. 7—OSCILLOGRAM OF "OCO" SHORT CIRCUIT TEST AT 12,000 VOLTS, 22,000 AMPERES R. M. S. ON 12,000-VOLT AIR CIRCUIT BREAKER

The integration constant C is therefore determined by the initial conditions $t = 0$ $i_1 = 0$ and the expression i_1 for the first loop of current (Fig. 4b) is found to be

$$i_1 = I_M\,[.348 \sin \omega t - .342 \cos \omega t + .342\, e^{-160 t}] \qquad (7)$$

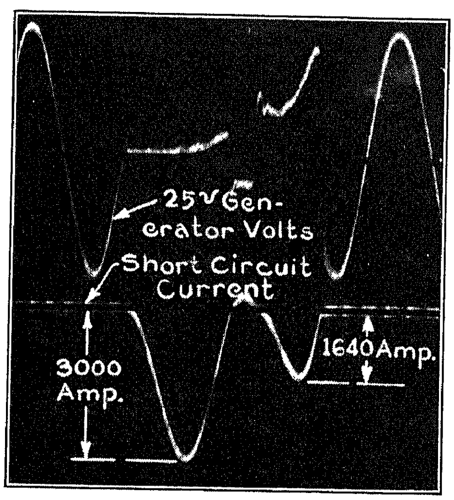

FIG. 8—OSCILLOGRAM OF 12,000-VOLT, 2700-AMPERE R. M. S SHORT CIRCUIT TEST ON AIR HIGH-SPEED CIRCUIT BREAKER

The voltage can be found by differentiating (7) for $\dfrac{d\,i_1}{d\,t}$ and substituting this and (7) in

$$E = i_1 R + L_1 \frac{d\,i_1}{d\,t}$$

for the case under consideration.

$$E = I_M\,[7.858 \sin \omega t + 4.105 \cos \omega t - 4.105\, e^{-160 t}] \quad (8)$$

The flux of the active transformer is determined from

$$E = 10^{-8}\, I_m\, N\, A\, \frac{d\,\Phi}{d\,t}$$

$$= [7.858 \sin \omega t + 4.105 \cos \omega t - 4.105\, e^{-160 t}] \quad (9)$$

Where N = number of turns on transformer secondary
A = area of core sq. cm.

$$\Phi = \frac{10^8\, I_M}{N\,A}\,[\,.0262 \sin \omega t - .0502 \cos \omega t + .0257\, e^{-160 t} + C] \qquad (10)$$

the initial flux is maintained at 13,000 lines per sq. cm. by the saturating direct current, therefore for

$$T = 0 \quad \Phi_0 = 13{,}000 = \frac{10^8\, I_M}{N\,A}\,[-\,.0502 + .0257 + C]$$

$$\text{and} \qquad C = -\,.0245 \qquad (11)$$

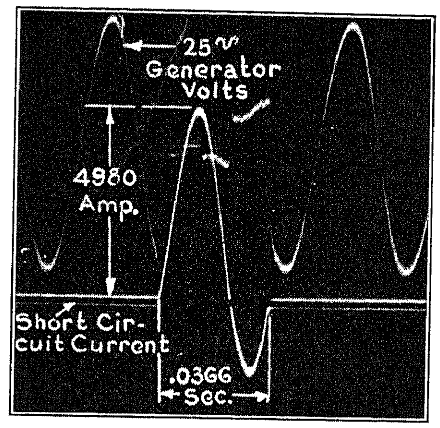

FIG. 9—OSCILLOGRAM OF A 3700 AMPERE R. M. S. 12,000-VOLT SHORT CIRCUIT TEST ON AN AIR BREAK CIRCUIT BREAKER

The flux curve calculated from (10) is shown by Fig. 4c.

It will be noted that at the time t_1 the current through the windings of the inactive transformer is reduced to the d-c. saturating current value, as the line current continues to increase during the second one-half cycle and a voltage is induced in the secondary winding of this transformer. From the flux curve of Fig. 4c, however, it will be seen that the flux of the previously active transformer has not yet returned to the saturation value and therefore there is a period from t_1 to t_2 where both transformers are active and present full transformer reactance to the flow of current and the total line current therefore flows through resistance R_2, (ignoring the exciting current for the transformers).

The flux change in both transformers for the period $t_1 - t_2$ is therefore determined by the voltage across the loading resistor R_2, Fig. 3a.

$$V = 10^{-8}\, I_M\, R_2\, N\, A\, \frac{d\,\Phi}{d\,t} = I_M \sin \omega t$$

$$\Phi = \frac{12 \times 10^8}{N A} [-\cos \omega t]$$

The corresponding flux curves for the period t_1 to t_2 until the flux of transformer No. 1 again reaches the saturation point, is shown on 4c. After saturation is

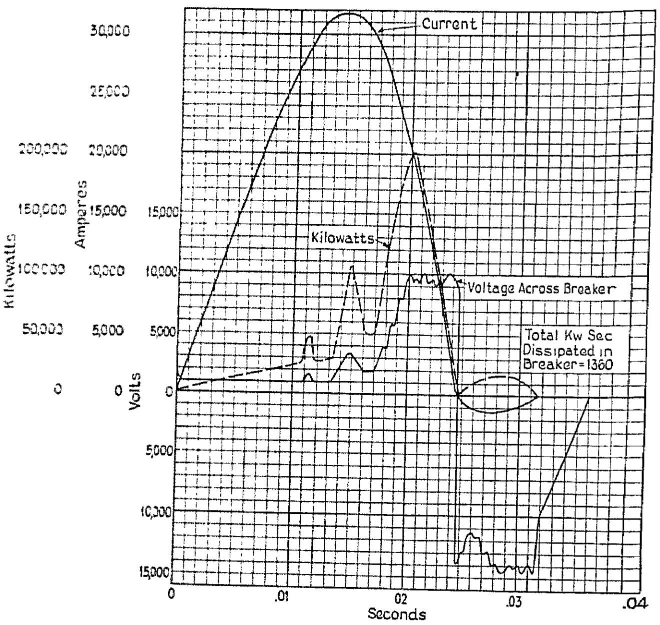

FIG. 10—CURVE TAKEN FROM OSCILLOGRAM FIG. 6, SHOWING KILOWATTS DISSIPATED IN THE ARC CHUTE OF AIR CIRCUIT BREAKER DURING A SHORT CIRCUIT TEST AT 14,000 VOLTS

reached, in the case of No. 1 transformer, a second current impulse is passed through the trip coil circuit by No. 2 transformer, the method of determination being the same as for the first impulse. At the conclusion of the second impulse, t_3, the flux of the second transformer is further from the saturation value than was the flux of No. 1 transformer at the end of the first loop and the line current again passes through R_2 until saturation is reached, the period from t_3 to t_4 being correspondingly greater than the period from t_1 to t_2.

In this manner the process is repeated, the period in which both transformers are active growing longer with each succeeding half cycle until a stable condition is reached where the flux is increasing through one transformer and decreasing through the other transformer for the full one-half cycle. When this occurs the sustained condition has been reached and no further current impulses are supplied to the trip coil so long as the line current is not increased. The full line current under steady state conditions passes through the resistance R_2.

The trip current supplied by this tripping circuit is approximately proportional to the increase in line current. Typical oscillograms showing the tripping current are shown on Fig. 11. The oscillograms of Fig. 11 were taken when applying an overload to the circuit which was previously carrying a steady load. The saturating current in this case was passed through an independent winding on the saturated transformers.

After the steady state condition is reached, should the line current be suddenly increased again, the saturation point is reached on one transformer as soon as the line current exceeds the steady state value and further current impulses are supplied through the tripping coil circuit.

VI. DESCRIPTION OF THE AIR BREAK CIRCUIT BREAKER

Photographs of a 12,000-volt 1500-ampere single-phase air break circuit breaker are shown on Figs. 1 and 2. A drawing of the principal parts of the mechanism is shown in Fig. 5. The armature, which is held in the closed position by a holding coil and released by a wire wound trip coil inserted between the poles of the holding magnet, is shown connected to the main high voltage contact arm through insulated pull rods.

The high voltage contact arms are operated entirely through suitable insulating pull rods, the mechanism being grounded. The circuit breaker as a whole consists of two sets of contacts and arc chutes which are connected in series, the moving contact arms being connected together by a suitable bus so that they form in effect a bridging contact similar to that used in oil circuit breakers.

There are two sets of springs, the main springs operating directly on the armature for opening at high

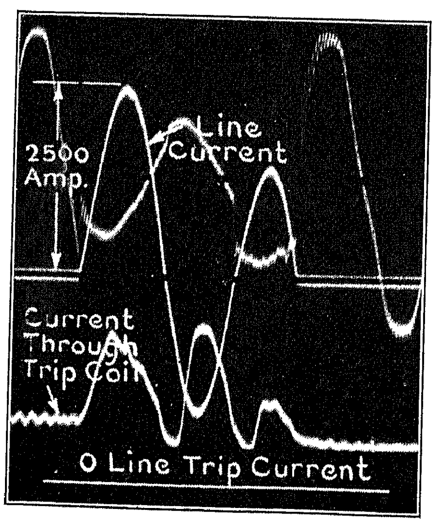

FIG. 11—TYPICAL OSCILLOGRAMS SHOWING CURRENT OBTAINED WITH SATURATED TRANSFORMER TRIPPING CIRCUIT FOR MAGNETIC TYPE OF HIGH-SPEED A-C. CIRCUIT BREAKER

speed while the contact pressure is exerted by a second set attached to the pull rods at the bottom of the arm.

This mechanism is inherently trip free, the operation being as follows:

Resetting is accomplished by means of a motor-operated cam. The first movement of the cam operates

the lever attached to the pull rods at the bottom of the contact arms rotating these arms about the top bumper as a fulcrum. The holding armature is pulled to the closed position by the main pull rods attached between the center of the contact arms and the bell cranks on the armature shaft. This armature is latched as the peak of the cam is reached without reducing the gap between contacts. Further movement of the cam allows the bottom springs to rotate the contact arm to the closed position around the top pull rods as a center.

The bottom of the arms when opening on short circuits, is held approximately stationary when opening by the weight of parts attached to the bottom. In the event the breaker is closed on a short circuit the mechanism therefore operates the contact at full speed regardless of the fact that the rollers have not yet left the cam surface.

The high voltage circuit through the breaker is very direct, entering on one side through series blow-out coils, one end of which is connected to a stationary contact. The circuit is completed through the moving contact and arm and another set of series blow-out coils from which the connection is made to the second contact mechanism, a duplicate of the first.

When the contacts separate under short circuit conditions, the arc is drawn on the arcing horns and detached blow-out coils are cut in successively as the arc travels along these horns. The general arrangement of the blow-out coils, arc suppressor plates, arcing horns, etc., is the same as that used on standard designs of 3000-volt d-c. breakers with the exception that a greater number of blow-out coils is used and the arc chutes are designed to permit a considerably longer arc.

A new feature which is introduced in this breaker consists of high resistance arcing horns made from a special material and designed to absorb a considerable voltage as the arc is forced along them under the action of blow-out coils. These arcing horns are effective in reducing the energy in the arc stream and in reducing the flame and noise of the breaker when opening under short circuit conditions.

Some typical oscillograms obtained during short circuit tests, including tests at 14,000 volts single phase, 25 cycle are shown in Figs. 6 to 9 included. The curves on Fig. 10 were plotted to show the current, voltage, and power relations during a short circuit test of 14,000 volts. It is interesting to note that the energy is liberated in the arc chute at a maximum rate of 200,000 kw.

The speed of operation of the mechanism taken with a mechanical speed recorder is shown by the curve on Fig. 12. It will be noted that total tip gap of more than 6 in. (two contacts in series) is reached in slightly more than the time required for a normal ½ cycle (25 cycle) after the trip point is exceeded.

VII. Current Rupturing Tests on Air Breaker

This breaker has successfully opened a current of 24,000 amperes r. m. s. at 14,000 volts repeatedly. A series of 20 OCO tests at 12,000 volts, 22,000 amperes, r. m. s. was made at two-minute intervals without examination or attention of any kind to the circuit breaker. A single contact and arc chute of this type of breaker, equivalent to one-half the standard 12,000-volt breaker has opened a maximum current of 41,000 amperes r. m. s. at 7000 volts repeatedly, both the tests at 14,000 and 7000 volts being the maximum available at the time the tests were conducted.

VIII. Selective Operation of the High Speed A-C. Breaker

Selective operation of high speed a-c. breakers applied to railway feeders is essential. The high-speed feeder breakers should isolate defective feeder sections between substations without disturbing power flow to adjacent interconnected sections under all short circuit conditions.

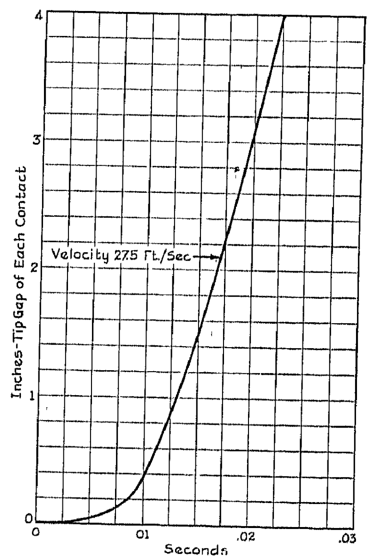

Fig. 12—Mechanical Speed of 12,000-Volt Air High-Speed Circuit Breaker

The connections shown in Fig. 13 are utilized for obtaining selective operation where the unidirectional current impulse type of trip is used. Advantage is taken of the unidirectional trip circuit in a differential connection. The tripping circuits of all breakers are connected to a common bus in such a way that the trip current circulating through any trip coil must return either through the trip coils of parallel breakers or the saturating resistor indicated on the diagram. When the current is increased simultaneously through all breakers feeding the feeders in a given direction from the substation, the tripping current for all of these breakers must pass through the saturating resistor shown on the diagram, since equal voltages are generated by the trip circuits of each breaker. The current required for tripping all of the circuit breakers under this condition is much higher than when the current is increased through one breaker only. By selecting a proper value

for the saturating resistor the current necessary for operation with a simultaneous current increase through all breakers can be made higher than the exchange current over the trolleys between substations in case of internal short circuit in one substation.

If the current is suddenly increased in one breaker only, by a short circuit on one feeder, tripping current is supplied to the breaker supplying the faulty feeder, this current returning through the coils of the remaining breakers and assisting to hold them closed. The tripping current for the breaker involved is considerably less than when all breakers carry current because of the lower impedance of the return circuit for the tripping current.

A simplified diagram showing breakers located in a typical feeder network has been shown in Fig. 14.

The operation of the breakers under typical short circuit conditions with connections as shown in Fig. 13 is as follows:

1. *Feeder Short Circuits.*

In the event of a short circuit on a feeder between substations, the breaker supplying this feeder carries a current considerably in excess of that of the parallel breakers since the parallel breakers carry the exchange current between substations only. Tripping current is supplied to the trip coil of this breaker, operating it, some of this current returning through the trip coils of the parallel breakers in reverse direction for tripping and assisting in holding them closed.

In the event of a feeder short circuit directly in front of one substation, all of the breakers in the distant substation carry equal currents until after the breaker in the near substation opens. The short circuit current is removed from all the breakers at the distant station by the operation of the breaker feeding the short directly,

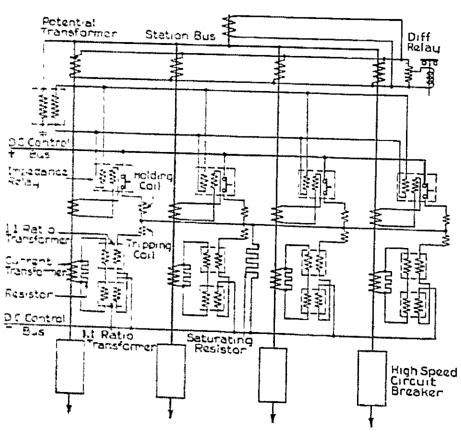

FIG. 13—DIFFERENTIAL CIRCUIT FOR SELECTIVE OPERATION OF FOUR MAGNETIC TYPE HIGH-SPEED CIRCUIT BREAKERS APPLIED TO A 12,000-VOLT TROLLEY FEEDER NETWORK

except the distant breaker feeding the faulty trolley. The current through this breaker is suddenly increased because of the removal of the heavy short circuit current from the high voltage transmission line and this breaker is operated, clearing the remaining short circuit.

2. *Substation Bus Short Circuit.*

In the event a short circuit occurs on the bus at a given substation, all breakers interconnecting the two substations carry equal exchange currents. These breakers are, therefore, not operated by the high speed

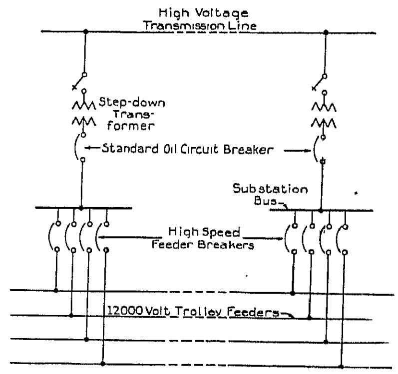

FIG. 14—SIMPLIFIED DIAGRAM OF A TYPICAL HIGH-SPEED BREAKER INSTALLATION ON A 12,000-VOLT RAILWAY FEEDER NETWORK

trip and the bus is isolated by the operation of a standard type of differential relay which opens all of the breakers connected to this bus. The feeders between substations are fed from the distant station and are not deenergized.

3. In case a short circuit occurs in the stepdown transformer or in the high tension line, the feeder breakers between the faulty substation and adjacent substation carry equal exchange currents and therefore do not receive a sufficiently high tripping current to operate. The faulty transformer or high voltage line is disconnected from the bus by the operation of a standard differential relay around the transformer or reverse power relays in case of a high voltage line short, both of which operate a circuit breaker on the low voltage side of the transformer.

CONCLUSION

The development of both air break and oil break 12,000-volt a-c. high-speed circuit breakers having a speed of operation comparable with the d-c. type makes possible the same degree of selectivity and protection on a-c. electrified systems as has been obtained for a number of years on equivalent d-c. systems.

It is expected that this type of breaker will be particularly beneficial in minimizing inductive interference in signal and communication circuits.

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Discussion

For discussion of this paper see page 1311.

High-Speed Circuit Breakers for Railway Electrification

From the Design Point of View

BY H. M. WILCOX[1]

Member, A. I. E. E.

FROM the point of view of switching service, circuit breakers as a whole may be divided roughly into general classifications dependent on the time required to isolate portions of the circuit under conditions of fault or to clear the circuit under any predetermined condition. Of these, the conventional normal-speed breaker constitutes by far the largest class in general use.

For d-c. switching service, this class is generally of the carbon-break type often applied in machine circuits with relatively high normal current loads requiring breakers of large current-carrying capacity with heavy moving elements. These breakers may be expected to interrupt a short circuit in from 0.07 to 0.10 sec. from the start of rise of short circuit current, although they are often used with a time-delay element intentionally placed in the control circuit to increase this time up to a full second or more. Where quicker action is desirable, particularly with breakers of lower current-carrying capacity, the contacts may be made trip-free from the closing mechanism and with a sensitive overload tripping device the time may be reduced to from 0.04 to 0.06 sec. The general form of the breaker, however, is not materially different in these two time classifications.

For a-c. switching service, the normal-speed oil circuit breaker is used over practically the entire range of service voltages. When actuated by a normal-speed relay, this breaker requires from 0.10 to 0.25 sec. after the occurrence of a fault to trip the breaker and interrupt the circuit. As in the case of the d-c. breaker, however, it is often used with a time-delay element in the control circuit extending the total time up to as much as three or four seconds. Where switching is mainly on the low side of the transformers the normal loads involved may require breakers of high current-carrying capacity with heavy moving elements, and for great concentrations of power the current rupturing requirements may be relatively high, calling for substantial sturdy construction of the contact details. When switching at higher voltages, the current loads become proportionately less, making lighter contacts feasible, and various forms of high speed contacts are used in which contact is maintained between arcing tips in the breaker until the main moving element has completed a considerable portion of its opening movement. The arcing tips are then snapped open at a high rate of speed independent of the speed of the main moving element, thus materially decreasing the duration of arcing. High-speed relaying is also resorted to where it becomes desirable to diminish the time between the occurrence of a fault and the drawing of an arc at the breaker contacts. In all of these forms, however, the breaker structures differ only in details and they may all be included in the same general classification.

During the last few years, the rapid advance in railway electrification work, particularly in the application of automatic features, has resulted in the development of a new class of breakers for this service known as high-speed circuit breakers. Developed largely for special protective purposes, these breakers perform a somewhat different function from that of breakers in other service for both of the two great classes of railway applications, d-c. and a-c. electrification projects. In time classification, high-speed breakers should function to interrupt a d-c. circuit in 0.02 sec. or less after the occurrence of a fault, and one cycle or less for a 25-cycle a-c. circuit.

In d-c. railway service, the synchronous converter operating at from 600 to 1500 volts occupies a commanding position as a medium for converting alternating current from the secondaries of transformers into direct current supplying feeder circuits for trolley or third rail service. This machine lends itself readily to automatic control without the necessity of an attendant, but is susceptible to flashing with considerable consequent damage to the commutating apparatus under short circuit conditions. To obviate this difficulty, the d-c. high-speed breaker has been developed to the point of interrupting a circuit before short circuit current can rise to its full value, and of so limiting the destructive period of duration of a short circuit as to preclude the possibility of flashing on the commutator. Fig. 1 shows a high-speed circuit breaker designed for 1500-volt d-c. railway service.

From the design point of view, certain characteristics must be incorporated in this breaker to meet the requirements for high-speed protection in d-c. circuits. The operating voltage for the majority of railway applications is 600, with a comparatively small number 1500 volts, so that a single break of from 1¼ to 1½ in. will be sufficient for the contacts when used in conjunction with an auxiliary magnetic blowout circuit.

1. Circuit Breaker Engg. Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

With careful attention paid to design of the contacts in order to reduce the air-gap in the blowout magnet to a minimum, a blowout value of the order of 20,000 ampere-turns at 5000 amperes will be sufficient where high-speed interruption is confined to current values of from 3000 amperes upward. For small kilowatt capacity machines, where high-speed action is desired for currents as low as 800 to 1000 amperes, blowout values must be materially increased to assure satisfactory results in operation.

Blowout values of this order may be expected to

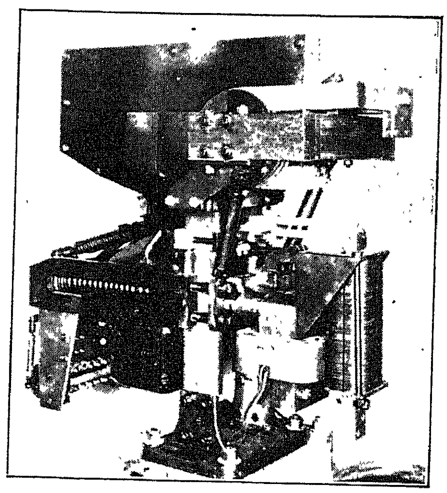

Fig. 1—High-Speed Circuit Breaker for 1500-Volt D-c. Railway Service, Circuit Rating, 3000 Amperes

remove an arc from the contact surfaces and transfer it to arcing horns during the first one-quarter inch of contact travel, so that all of the mechanical force applied to produce acceleration of the moving contact on opening should be concentrated so far as possible in this first one-quarter inch of travel and no further interest need attach to the speed of contact opening beyond this point except to insure that there is sufficient contact separation at the time the arc is extinguished to prevent reestablishment of the circuit. The problem then becomes one of acceleration rather than of high speed, since the accelerating force, while quite large, is not applied for a sufficiently great length of time to produce relatively high speeds. Fig. 2 shows the speed of contact travel at various points in the opening stroke up to one inch on a high-speed breaker designed for 3000 ampere d-c. service.

From this it will be apparent that for d-c. service, any feature which detracts from the amount of contact opening during the first 0.004 sec. after the breaker is tripped will hinder the limitation of current very materially. For instance, an auxiliary arcing contact with a quarter-inch lead would result in a complete loss of this time and a flexible brush contact involving an eighth-inch follow-up would result in a loss of nearly 70 per cent of it. Consequently, where feasible, a solid butt contact without auxiliary arcing tips becomes very desirable. Such a contact also permits working to a much higher current density, resulting in a very considerable reduction in the mass to be accelerated since there is no flexible laminated copper present to suffer possible deterioration under excess temperatures. Given a design in which the flexibility necessary to secure adequate contact pressure is supplied by a spring, working through leverage if necessary, the solid butt contact becomes entirely feasible for this application.

The resulting design is, then, a solid butt contact which carries main-circuit current, on which the arc is drawn as soon as mechanical separation of the contact surfaces is obtained, and from which the arc is transferred to arcing horns very early in the opening stroke by a powerful blowout magnet. These arcing horns are an integral part of the arc chute and care must be taken in the design to arrange them so as to secure the greatest possible increase in the length of arc in the shortest interval of time. Test data indicate that a d-c. arc becomes unstable at potentials in the order of 30 to 35 volts per in. of length which would require stretching a 1500-volt arc to a length of approximately 45 in. for interruption. The arc chute for a 1500-volt breaker must then be designed to accommodate an arc of this length with sufficient additional capacity to cover such overvoltages as may be encountered on highly inductive circuits without permitting the arc to extend outside of the chute to such an extent as to strike other potential points. Care must be taken also in the design of pole faces to secure a properly graduated blowout field over the arcing area. This field must be intensified at the point of origin of the arc, but must shade off rather rapidly after the length of arc has

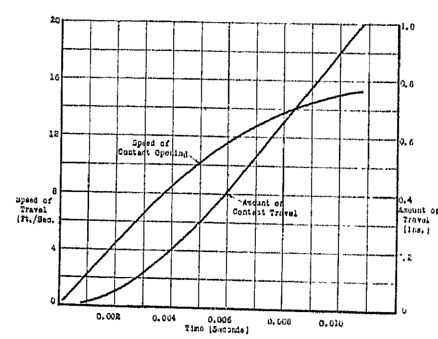

Fig. 2—Speed of Contact Opening for High-Speed D-c. Circuit Breaker. Current Capacity, 3000 Amperes

reached a point corresponding to the limitation of current rise in order that the rate of fall of current may not be too rapid as the interrupting point is approached. Tests with breakers of this type indicate that a very fast falling current may be accompanied by an overvoltage surge of such magnitude as to cause severe potential stresses on the machine. From this point of view, a breaker which interrupts a given circuit in 0.015 sec. may impose materially less stress on the machine than one which gives complete interruption in considerably less time.

From time to time, various arrangements of arc splitters have been incorporated in d-c. arc chutes in an attempt to supply a mechanical means of lengthening the arc rapidly. Difficulty has been encountered in the use of such splitters due to their choking the expulsion of gases from the vicinity of the contacts with consequent re-ignition of the circuit across the points of the arc splitters or across the contacts themselves. The tendency in modern breakers is toward the removal of all obstructions in the chute to permit the free action of convection currents following the rise of the arc and thus provide adequate ventilation for removing the gas field from the vicinity of the contacts as the arc extends.

As to mechanical operation of the contacts, the breaker must be capable of high-speed interruption in the event of being closed against a fault in service, which requires that it be trip-free in action. This is best accomplished by a multiple-stage closing stroke through a floating lever. Fig. 6 shows the arrangement of such a mechanism in which the closing power is applied at one end of the floating lever and utilized to seal the holding armature while the contacts remain in the open position. A set of closing springs is also extended by this closing solenoid stroke. Upon de-energizing the solenoid, these closing springs serve the threefold purpose of closing the contacts, extending the opening springs, and retrieving the solenoid core. Thus by utilizing various pin centers in the floating lever as fulcrums at different stages of the movement, the contacts become trip-free at any point in the closing stroke. The excess of power in the closing springs over that of the opening springs provides the flexible means necessary for maintaining adequate contact pressure referred to previously. While tending to maintain the contacts in the closed position, these closing springs in no way hinder the opening movement since the point at which the holding-in power is applied becomes a fulcrum for the opening movement as soon as the holding armature is released.

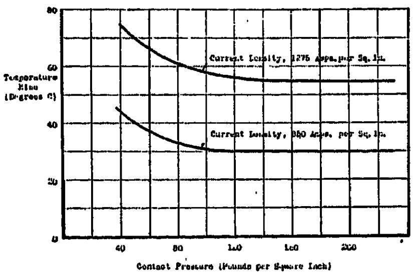

FIG. 3—RELATION OF TEMPERATURE RISE TO CONTACT PRESSURE FOR SOLID BUTT CONTACTS IN AIR

Fig. 3 shows the effect of contact pressure on temperature rise with the use of solid butt contacts in air for current densities per square inch of contact surface of the order of magnitude ordinarily used in breakers of this type for railway service. It will be noted that the temperature rise decreases quite rapidly with the increase in pressure through the lower range but the decrease is less marked at pressures of from 80 to 100 lb. and very little improvement is shown beyond this point for pressures up to well over 200 lb. per sq. in. From these curves it will be apparent that the method of securing contact pressure by maintaining a balance between two springs may be relied upon to give adequate pressure, and at the same time provide a considerable range in adjustment of the springs for other purposes. Comparative tests have been made to determine the ability of this type of contact to carry heavy current loads after repeated drawing of arcs from the main contact surfaces. The temperature rise was determined by test for a breaker with new contacts worked at a current density of approximately 1200 amperes per sq. in. of contact surface, and a second test made on the same breaker after it had been used for short circuit test purposes until the contact surfaces showed no indication of their original machining, and without any cleaning of these surfaces. This second test showed approximately 15 per cent less current density for the same temperature rise. The contacts should, then, be designed with sufficient factor of safety to permit an equivalent increase in temperature rise before reaching final temperatures at which deterioration of the contact material may begin.

In view of the rigid requirements as to time for the operation of high-speed breakers in d-c. circuits, the delay involved in releasing a mechanical latch of the conventional type becomes a severe penalty when this device is used. An arrangement which has been found well adapted for retaining the d-c. high-speed breaker in its closed position comprises a stationary holding magnet and an armature linked to the operating levers, so arranged that upon the decay of holding flux, due either to the interruption of holding current or to demagnetization from some other source, the armature will release and permit the contacts to open under the influence of the opening springs. As the armature must be given a high rate of acceleration, its mass will be reduced as much as possible, resulting in its being worked well up toward the knee of the saturation curve.

This being a protective breaker, designed to limit the rise of short circuit current in the shortest possible interval of time after the occurrence of a fault, some form of tripping other than simply the consequence of amperes of overload becomes essential. An overload device is inherently unable to determine whether or not a load is to become a hazard until it has already reached the hazardous point, and this in the case of a short circuit of fast-rising current is far too late to limit that rise satisfactorily. A discriminating device known as an inductive shunt, whose action is based on the rate of rise of current, is best adapted to the requirements. The main power circuit in the vicinity of the holding magnet is divided into two parallel paths, one of which passes through the air-gap of the holding

magnet while the second by-passes this magnet. Under conditions of steady load or of slowly-rising load, the by-pass lead carries a relatively large proportion of the current and the air-gap lead a small proportion which, due to the arrangement of potentials, produces a flux in the holding armature opposed to that generated by the holding coil current. So long as steady conditions or slowly-rising conditions obtain, the holding coil predominates and the armature holds the contacts in the closed position. The by-pass lead is, however, so arranged as to be acted upon by a laminated iron circuit which in the event of a rapid rate of rise in current acts to force a comparatively large proportion of the load through the air-gap lead momentarily. This results in a sudden increase in the demagnetizing flux in the holding armature which releases it and allows the contacts to open due to the action of the opening springs.

It will be apparent that with this arrangement, a

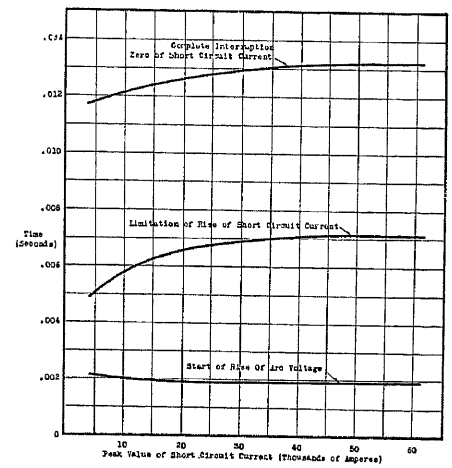

FIG. 4—TIME CHARACTERISTICS OF HIGH-SPEED D-C. CIRCUIT BREAKER ON SHORT CIRCUIT TEST, AT 600 VOLTS

balance may be secured between the holding coil flux and that generated by the action of the inductive shunt so sensitive as to permit the breaker to open with very slow rates of rise of main circuit current. General operating conditions in d-c. railway service, however, require that the high-speed breaker shall not open on legitimate changes in load such as the acceleration of a train, and some point just above the fastest rate of rise obtainable from train acceleration becomes the lower limit at which this breaker may be allowed to open under changing load conditions. It will be understood that in operating service a fault may occur which due to circuit conditions, generally a matter of distance from the station, gives a rate of rise of short circuit current less than the rise from nearby heavy train acceleration and that the high-speed breaker may not be expected to interrupt such short circuits when the balance between holding and demagnetizing flux is so arranged as to open only on a higher rate of rise. Some other discriminating device must be installed in the circuit for this purpose. It will also be obvious that this degree of sensitivity in the breaker may be dulled further over a wide range until the point is reached where it has become practically an overload breaker with no discriminating characteristics and with very little ability to protect a commutating machine. It should be borne in mind that where this type of breaker is applied for the performance of functions

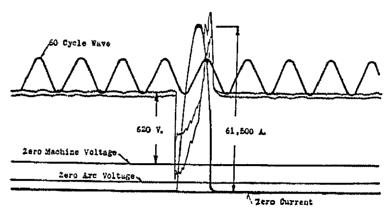

FIG. 5—OSCILLOGRAM SHOWING PERFORMANCE OF HIGH-SPEED D-C. CIRCUIT BREAKER ON OCO DUTY CYCLE

other than opening on rate of rise of current, some degree of discrimination will be sacrificed with a corresponding loss in the protective function for which it was primarily designed.

Fig. 4 shows the time characteristics of a high-speed d-c. circuit breaker over a considerable current

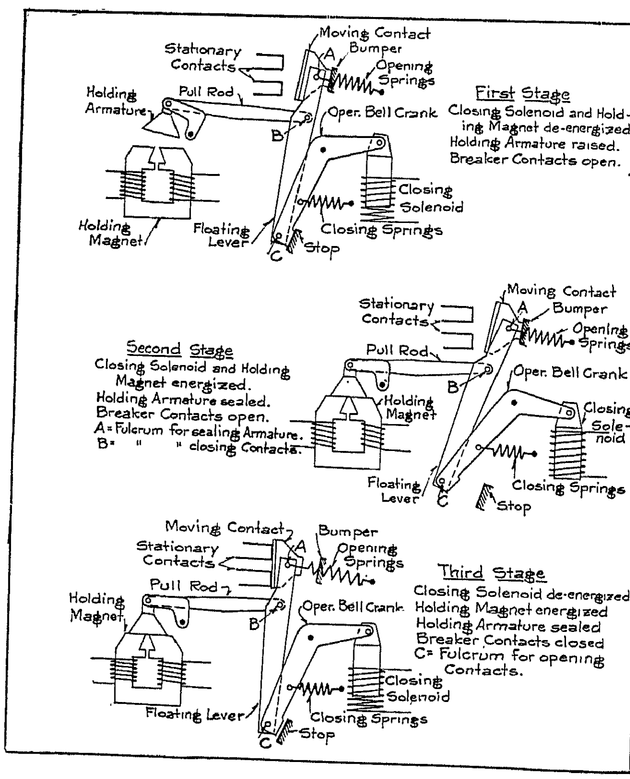

FIG. 6—DIAGRAMMATIC SKETCH SHOWING MULTI-STAGE CLOSING MECHANISM FOR HIGH-SPEED, TRIP-FREE ACTION

range at 600 volts. For current rises of from five million amperes per second upward, for d-c. voltages up to 1500, these breakers may be expected to limit the rise of short circuit current in from 0.006 to 0.008 sec. and to interrupt the circuit completely in from 0.012 to 0.016 sec. Tests on a 600-volt synchronous

converter substation giving a current rise of the order of thirteen million amperes per second show limitation of short circuit current across the buses to slightly less than 300 per cent of normal load. For machines whose characteristics give a slower rate of rise such as a d-c. generator, the time of limitation and interruption of current will be proportionately longer while still providing adequate protection to the commutating apparatus. Fig. 5 is an oscillographic record of high-speed breaker performance on heavy current at 600 volts.

For alternating-current railway service, the high-speed breaker assumes an entirely different form. The majority of such applications today are main-line electrification projects fed from overhead contact lines at 11,000 volts, 25 cycles, with frequent movements of heavy trains. On such applications the use of high-speed breakers capable of limiting the duration of short-circuit current is of considerable advantage in lessening the shock to the system, in reducing the damage to contact lines, and in minimizing the possibility of synchronous machines falling out of step. Furthermore, the use of high-speed breakers facilitates the coordination of propulsion and communication circuits when they are involved in an inductive exposure. As this propulsion service is almost entirely confined to a frequency of 25 cycles, one-cycle operation allows 0.04 sec. for the detection and interruption of a short circuit. The high-speed circuit breaker shown in Fig. 7 has been developed to meet the requirements of such applications. Essentially a single-pole oil circuit breaker of the conventional gravity break type, it differs from the normal-speed oil breaker in that it carries: a high-speed shunt-tripping device; provision for a high acceleration of the moving contact; an auxiliary magnetic blowout circuit for lengthening the arc rapidly; it is actuated by a specially-designed high-speed relay. Unlike the d-c. high-speed breaker, it carries no discriminating features in itself but is actuated solely by the high-speed relay in which are incorporated all the characteristics necessary for such selectivity in tripping as may be desirable for any given application. The breaker carries a voltage rating of 15 kv., although all electrical clearances outside the interrupting chamber are adequate for 37-kv. service. It is designed for steady current loads of 1500 amperes at 25 cycles, and has an interrupting capacity of 50,000 amperes at 12 kv.

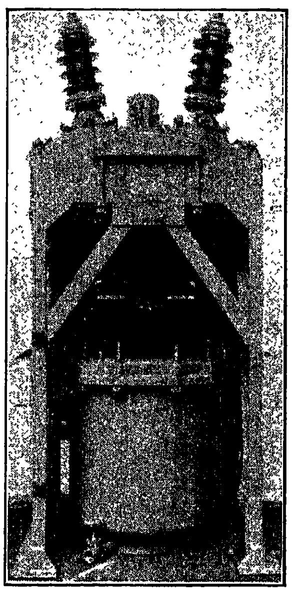

Fig. 7—Front View of High-Speed Circuit Breaker for A-c. Railway Service, Rating 15 Kv., 1500 Amperes, 25 Cycles

From the design point of view, this breaker presents a problem somewhat different from that involved in the d-c. high-speed breaker. The holding magnet raises problems due to directional characteristics when applied to a-c. circuits that require considerable in the way of added complications to overcome. Furthermore, this form of tripping does not carry inherently the degree of selectivity desirable for the majority of a-c. railway applications and some additional relaying becomes advisable when it is used. Consequently, a quick-acting mechanical latch released by a high-speed trip magnet, which in turn is actuated by a high speed selective relay external to the breaker, becomes not only feasible but desirable from the point of view of close accurate settings for selective tripping.

For like reasons the contacts in this breaker may be designed differently from those of the d-c. high-speed breaker. To perform the function for which it was developed, the breaker is placed in the contact line feeder circuits where the current loads are relatively light as compared with the heavy machine loads of d-c. railway circuits. The flexible brush form of contact may be used here without imposing great burdens in the form of mass, to be accelerated at high speed, provided the brush is used as the stationary element of the contacts. By a liberal design of this stationary element, the moving element may be worked at a comparatively high current density, depending on the stationary copper to conduct heat away, and the mass to be accelerated thus reduced to proportions that may be handled with reasonable facility.

The breaker must be trip-free in order to interrupt the circuit at high speed in the event of being closed against a fault. In the conventional form of oil circuit breaker the trip-free point is normally placed at the closing mechanism in order to combine the closing and tripping features in a single unit and to insure simultaneous action in all phases of a multiple-pole breaker. In this country at the present time, a-c. railway applications are, however, practically all on a single-phase basis so that a single-pole breaker meets all requirements. The trip-free point may then be placed as close to the moving contact element as mechanical and electrical requirements will permit, provided the tripping mechanism is placed at this point also. The point best

suited to all these conditions will be found at the upper end of the contact lift rod, requiring only the contact, its lift rod, and one lever to be accelerated on opening. The accelerating force may be supplied by a helical spring concentric with the lift rod.

Fig. 8 shows in graphic form the accelerating force in pounds for each pound of mass accelerated necessary to produce various speeds at the end of the first one-quarter inch of contact travel in oil. It may be noted that approximately one-third of the mass of the spring itself must be included as mass to be accelerated when designing these springs. As in the case of the d-c.

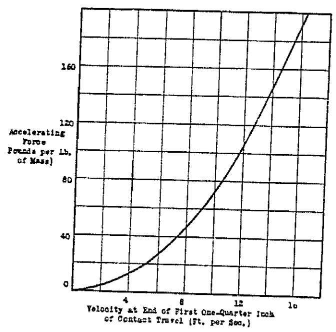

Fig. 8—Relation of Accelerating Force to Contact Velocity. (In Oil)

breaker, this is a problem of high acceleration rather than high speed of travel since interest in the speed of opening is confined largely to the first one-quarter inch of travel, that is, the amount of travel necessary to part the contacts and produce an arc. Through the

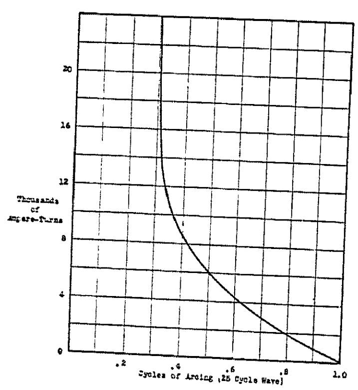

Fig. 9—Variation in Duration of Arcing with High-Speed A-c. Circuit Breaker for Varying Values of Magnetic Blowout Field

action of the blowout magnet, this arc will be transferred to arcing horns and lengthen rapidly independent of the speed of contact travel. Of course, one terminal of each arc must be maintained on the moving contact, but tests have demonstrated that with the moving contact shaped to provide a horn, the arc terminal will travel on this horn ahead of the contact under the action of a blowout field.

Fig. 9 shows the effect of a blowout field on the duration of arcing in a high-speed oil circuit breaker. The effect is quite marked for the lower values of field strength but the curve finally becomes asymptotic as the field is increased in strength and a point is eventually reached at which no further reduction is obtained in the period of arcing by increasing the excitation of the blowout magnet. This point, however, is well within a half-cycle of arcing on a 25-cycle wave and meets the requirements of present-day a-c. railway service.

The design of the blowout magnet will vary somewhat depending on the service in which the breaker may be applied. Where only low values of short-circuit current are to form a large proportion of the interrupting duty, a full iron return circuit may be used to work well below the saturation point. If heavy short circuits are anticipated, better results will be obtained with a magnet having a small section of return circuit designed to saturate at six to eight thousand amperes and forcing an air return path for the high current values. This is in order to eliminate the possibility of lengthening the arc unduly fast for very high current values having a heavy blowout force inherent in themselves. Care must also be taken in the design of this magnet from the point of view of temperature rise, bearing in mind that it must be excited by a series a-c. coil, and adequate means provided for radiation of heat. In this connection it may be noted that this application in railway service imposes a duty on trolley feeder breakers somewhat more severe than the standard N. E. M. A. duty cycle in that they may be called upon to perform more than the stipulated two OCO operations at full rated current, or a proportionately greater number at lesser current values, before an opportunity is afforded of renewing the oil. Provision should then be made in the design for a substantially larger amount of oil in the interrupting chamber than is required for conventional breakers of the same interrupting rating, and this increased body of oil will be of material benefit in taking care of heat radiation.

The design of mechanical latch for retaining the contacts in the closed position must receive careful attention in order to insure that the time of unlatching is reduced to a minimum. The conventional form of circuit breaker latch with right-angled holding face involves inherent time delay in that the holding face must be moved well over the center of the roller before opening motion can start. With the heavy accelerating spring used, this form may also result in heavier latch loads than are desirable for high-speed tripping.

Fig. 10 shows the details of a high-speed latch mounted in a common frame with the tripping magnet, forming an integral unit. The roller element of this latch is mounted on a floating lever linked to the contact lift rod and accelerated with it on opening. The primary latch presents an inclined surface to this roller in such manner as to give an angle of thrust well inclined toward the open position so that the movement of the floating lever and roller in opening starts simultaneously with the movement of the latch in releasing. This primary latch is maintained in the closed position by a secondary latch requiring only about one-eighth

of an inch movement to release. In operation, the tripping magnet raises the secondary latch, allowing the primary latch to release under the impulse of its own latch load and at the same time permitting the floating lever and contact to start toward the open position. The floating lever is retrieved to the latched position with the contacts open and revolved about the latch roller as a fulcrum to the closed contact position by the closing mechanism. An over-center toggle in the operating linkage maintains the breaker in the closed position until it is again tripped. Thus, by utilizing different centers in the floating lever as a ful-

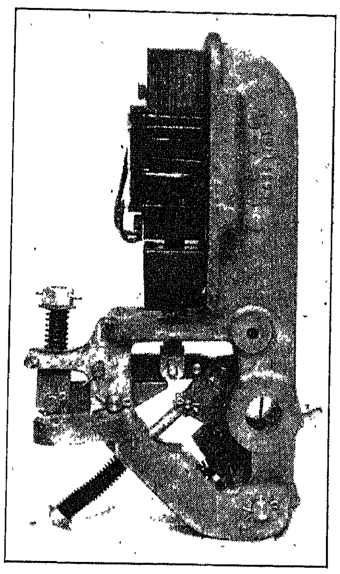

FIG. 10—SHUNT TRIPPING MAGNET AND LATCH FOR HIGH-SPEED A-C. CIRCUIT BREAKER

crum at different stages of the movement, trip-free action is obtained at any point in the closing stroke.

A d-c. shunt tripping magnet designed for use with the high-speed oil breaker is shown in Fig. 10. This magnet while necessarily enclosed within the breaker chamber, should be so located as to be freely accessible upon the removal of a cover in the main breaker casting. Fig. 7 shows a view of the breaker with the cover removed, exposing the magnet. This magnet is of the conventional laminated form, rather liberal in design so far as the magnet itself is concerned, but with the mass of the armature reduced to a minimum since it must be picked up very quickly. With the design of latch used here, the air-gap may be reduced to about five-sixteenths of an inch with a working travel of from one-eighth to three-sixteenths. To obtain the most suitable magnet, a low resistance coil will be necessary but external resistance may be used in the circuit where it is desired to maintain tripping current within the limits of battery supply for simultaneous tripping of a number of breakers.

Fig. 11 shows a view of the mechanism housing of a high-speed a-c. breaker with the covers removed. A closing solenoid, designed for 125-volt d-c. control, is mounted as an integral part of the breaker unit together with the necessary control panel, rotary type auxiliary switches, and a heater unit to prevent condensation inside of the housing under certain atmospheric conditions. As in the case of the d-c. high-speed breaker, such auxiliary switches as operate in unison with the main breaker contacts are moved to one

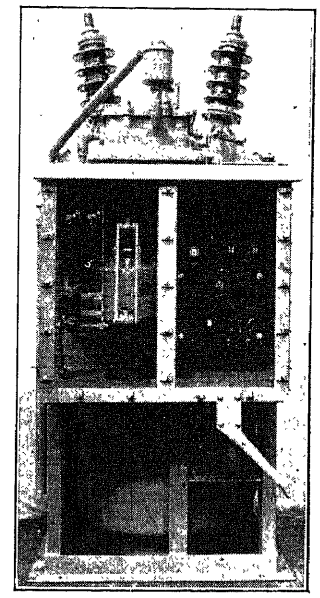

FIG. 11—REAR VIEW OF HIGH-SPEED CIRCUIT BREAKER FOR A-C. RAILWAY SERVICE SHOWING CONTROL MECHANISM

position by a linkage operated by the closing of those contacts but on the opening of the breaker contacts, are retrieved to the opposite position by a spring. This is to reduce the load on the main accelerating spring when opening as well as to relieve the switches of the mechanical stresses incident to high-speed operation.

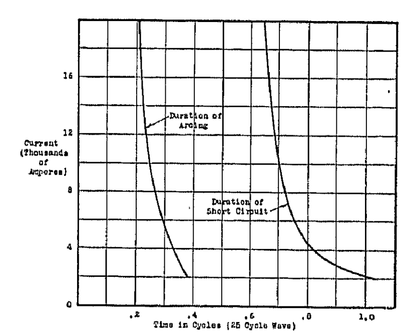

FIG. 12—TIME CHARACTERISTICS OF HIGH-SPEED A-C. CIRCUIT BREAKER ON SHORT-CIRCUIT TEST.
Including Time of Relay and Shunt Trip

Fig. 12 shows the time characteristics of a high-speed a-c. circuit breaker on short-circuit test, including the operating time of the high-speed relay and shunt trip. This breaker is designed to interrupt short-circuit currents of from 2000 amperes upward in 0.04 sec. (one cycle on a 25-cycle wave) after the occurrence of a fault. For current values of from 15,000 amperes upward, the breaker operates rather consistently in one-half cycle when the short circuit originates at or shortly after the zero point of the wave. In the

event of the fault occurring relatively late in any given half-cycle, it will often persist through the next half-cycle before interruption. For current values of less than 2000 amperes, the time of interruption will still be of the order of one cycle but due to the inherently low blowout values involved as well as the necessity of varied relay settings to secure selectivity, the short circuit may persist for an additional half-cycle. Tests made at current values of from 10,000 to 15,000 amperes over a voltage range of from 1500 to 12,000 volts show no appreciable difference in the duration of arcing, indicating that within the range of service voltage in present-day railway applications, the time of circuit interruption for a breaker of this type is independent of initial circuit voltage. Fig. 13 is an oscillographic record of performance on short-circuit test at 11,000 volts.

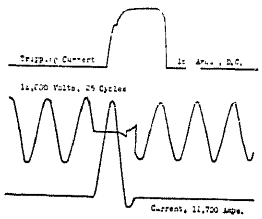

Fig. 13—Oscillogram Showing Performance of High-Speed A-c. Circuit Breaker on OCO Duty Cycle

A word as to the problems confronting the design engineer in attempting to apply high-speed breaker operation of this type to higher a-c. voltage service or to multiple-phase circuits. It has been pointed out in this paper that an auxiliary blowout field is essential to high speed interruption at the lower current values. Obviously, to be efficient the blowout field must be so distributed as to supply not only an intense field at the point of origin of the arc but also a properly graduated field over the whole area in which the arc may exist at any stage of its interruption. As the service voltage increases, requiring the drawing of longer and longer arcs to rupture the circuit, these magnets must control ever increasing areas, becoming in themselves more and more unwieldly to support in the breaker chamber with adequate insulation clearances. As the magnetic structure thus extends farther and farther downward into the clear break distance in the open position of the contacts in the effort to control the arcing area, the travel of the contacts must be increased by a safe amount to secure the necessary break distance for preventing reestablishment, thus increasing the over-all height of the breaker structure and, incidentally, its cost. As we approach the point in service voltage at which static shielding becomes necessary, these problems become so serious as to suggest seeking some method of securing the desired circuit conditions other than by the use of high-speed breakers.

As to application in multiple-phase circuits, it is obviously unsafe to permit the contacts of any single pole of a multiple-pole breaker to be operated independently of the other poles. This means that the tripping point must be so located as to control all of the linkage inside of all pole units as well as such linkage outside of these units as may be necessary to operate the several poles from a central point. This involves at once an increase of many times the mass to be accelerated at high speed and calls for a class of mechanical design not hitherto used to any extent in switching apparatus. At the best, there must be a very material increase in the power of accelerating springs used, and this power must again be reflected in increased closing loads creating an additional problem not only of design but of application as well.

In general the conclusion may be drawn that from the design point of view, adequate high-speed circuit breakers can be supplied to meet the present-day requirements for machine protection in d-c. railway circuits as well as such requirements as may be foreseen for some time to come. Also, adequate high-speed circuit breakers can be supplied to meet the requirements for protection for 25-cycle, single-phase, railway electrification work up to 12,000 volts. High-speed a-c. breakers for the next one or two steps above this in operating voltage for single-phase railway service seem within easy reach although not developed at the present time due to an absence of demand for breakers at these voltages. A-c. breakers of this type for high-tension circuits, or for multiple-phase circuits at any voltage are not at the present time available, and seem to present problems requiring a substantial amount of development work before they may become available.

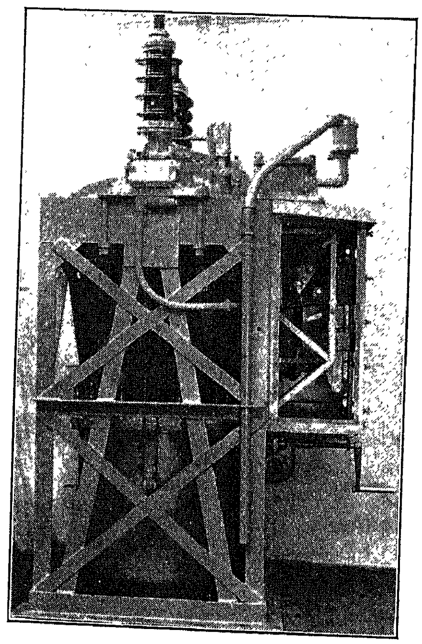

Fig. 14—Side Elevation of 15-Kv., High-Speed Circuit Breakers for A-c. Railway Service

Discussion

For discussion of this paper see page 1311.

Operating Experience with High-Speed Oil Circuit Breakers

BY B. F. BARDO[1]
Non-member

Synopsis.—*This paper outlines the experience of the New York, New Haven and Hartford Railroad with three high-speed oil circuit breakers which were installed in 1925 to serve an electrified branch line carrying freight and passenger traffic, both local and through.*

Satisfactory operation of paralleling commercial communication circuits, as well as of its own, presented an immediate problem, which after study outlined in the paper, finally yielded, and the answer, in part, was high-speed circuit breakers. The electrical and mechanical characteristics of these are set forth in detail and illustrated.

A number of tests of the circuit breakers and communication circuits made by short-circuiting the 11,000-volt lines on the branch showed currents up to 3000 amperes, and openings in from one-half to one and one-half cycles, with satisfactory operation of commercial and railroad communication plant.

A detailed record of the service operations of the circuit breakers along with a statement of failures is given. It is proper to say that the latter were more numerous in the early days of their use than they have been in recent months, and that a number of the faults are chargeable to the railroad's urgent need for the equipment, thereby considerably limiting the development and testing time desired by the manufacturer.

While it was not discussed in detail in the paper it goes without saying that in the design and installation of the circuit breakers safety was a paramount consideration. The illustrations will provide an index of this in the general arrangement of equipment, and also in the screen placed horizontally around the structure at the floor level to prevent curious small boys from climbing in to investigate.

Character of Service and Electrification

Before discussing in detail the New Haven Railroad's experience with high-speed oil circuit breakers, it will be of interest to review briefly the reasons for their installation.

In the latter part of 1924, decision was made to electrify the Danbury Branch, comprising 23.82 mi. of main, along with 5.1 mi. of passing or side track between South Norwalk, Conn., in the New Haven's electric zone, and Danbury, Conn. The service at that time consisted of an average of six passenger trains, two through freight trains, one milk train, and one local freight train per day in each direction. The system of electrification was to be essentially the same as that in use on the main line, between New York and New Haven, Conn., namely, 11,000 volts, single-phase, 25 cycles, using an overhead contact wire and track rail return. A schematic diagram of the distribution system, as finally adopted, is shown in Fig. 1.

Communication Facilities

On the branch to be electrified the New Haven had open wire communication circuits used by the Western Union Telegraph Company and itself respectively. Furthermore, on private property immediately adjoining and paralleling the company's right-of-way for nearly half of the distance and on public highway for the balance of the distance was a commercial open wire telephone line, this being more or less spread out in the various towns along the way. Therefore, an immediately important problem was to decide how best to provide for satisfactory operation of paralleling commercial and its own communication circuits, and at the same time not make the electrification itself too involved, from an operating standpoint, or too expensive from a maintenance standpoint.

Studies Made

Various schemes were studied involving the use of reactors in the trolley and feeder circuits at South Norwalk (see Fig. 1), along with booster transformers, balancing transformers, and supplementary return circuit, independent of the running rails, the induced

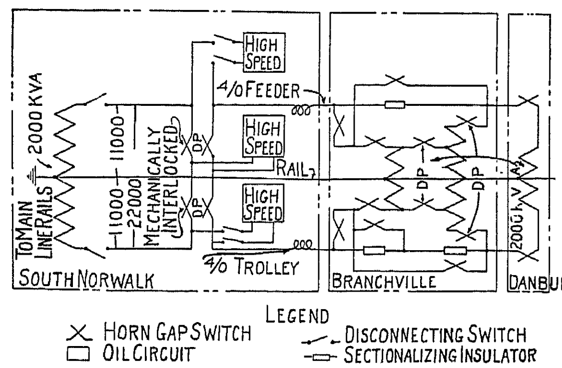

FIG. 1—NEW YORK, NEW HAVEN & HARTFORD RAILROAD COMPANY, DANBURY BRANCH

Schematic diagram of electric power distribution

voltages and other effects in each case being based upon the average duration of short circuit as determined by oil circuit breakers standard elsewhere in the electrified zone. The results of these studies indicated that the electrification and the communication circuits could be so designed that they would operate satisfactorily, using existing standard circuit breakers to interrupt short circuits, but this involved the installation of a number of series booster transformers, which were not desirable from railroad operating point of view.

At this point the installation of high-speed oil circuit

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Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

breakers at South Norwalk was proposed, with the understanding that while they would not decrease the magnitude of the voltage induced in the communication circuits, yet by virtue of their quick operation, they would materially reduce interference in both railroad and commercial communication circuits. It was decided that circuit breakers of this kind would be more desirable than booster transformers, and therefore the following program, satisfactory to all interests, was adopted:

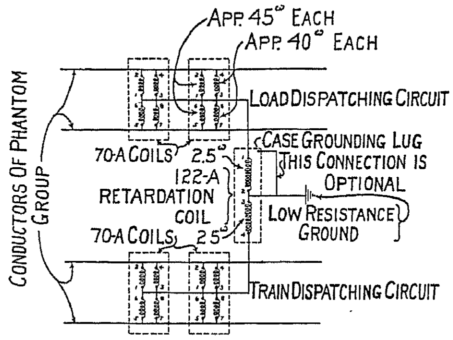

Fig. 2—Danbury Branch—Communication Circuit Drainage

a. Place paralleling commercial communication circuits in cable on the public highway.

b. Install adequate drainage on communication circuits on railroad right-of-way—Fig. 2.

c. Install high-speed oil circuit breakers at South Norwalk together with three-ohm reactor, in trolley and feeder circuits respectively, and auto balancing transformers at South Norwalk, Branchville, and Danbury,—the one at Branchville to have incorporated with it an auxiliary unit capable of raising the voltage approximately ten per cent. See Fig. 1.

Description of Circuit Breakers

The matter of deciding to use high-speed oil circuit breakers proved to be more simple than procuring them. Some development work had been done, but the circuit breaker was not then in commercial production, and considerable pressure was required to convince the manufacturer that three should be built. This, however, was finally arranged, and they were built early in 1925.

Each of these carries a normal rating of 800 amperes at 16,500 volts, 25 cycles. The maximum interrupting capacity approximates 35,000 amperes. Direct current is used for control normally at 250, but with a standby supply at 500 volts. The tripping operation is started by solenoids, of which there are two, connected in parallel on the lower, and in series on the higher voltage. The actual tripping work is done by spiral springs, these being compressed during the closing operation by a 110-volt, 25-cycle, single-phase motor operating through a train of gears. The circuit-breaking mechanism is in the shape of an inverted letter "T," with a blowout coil, in series with the circuit to be broken, on each stationary contact. The entire assembly is immersed in insulating oil, and enclosed in a substantial sheet steel cylindrical tank, suitably vented. Two condenser type bushings, each terminating in a removable stationary contact within the tank carry the current, and the whole is supported by four angle steel legs to which are bolted cast iron feet. There is an individual current transformer of the outdoor type for each circuit breaker, which is directly connected to an overload coil, also for each circuit breaker. Irrespective of the location of the short circuit, whether on trolley or feeder, it is desirable to open both trolley and feeder circuit breaker, and this is accomplished by auxiliary contacts on each overload relay so connected that when one circuit breaker opens the other will immediately follow, thus clearing the line.

Installation

Three circuit breakers were installed on a steel platform 27 ft. by 10 ft., with reinforced concrete house directly underneath, and change-over horn-gap switches directly overhead. Reference to Fig. 1 will show that any of the three circuit breakers may be used in any combination, two at a time. Fig. 3 shows an elevation of circuit breakers as installed, and Fig. 4 of the entire substation of which they are a part.

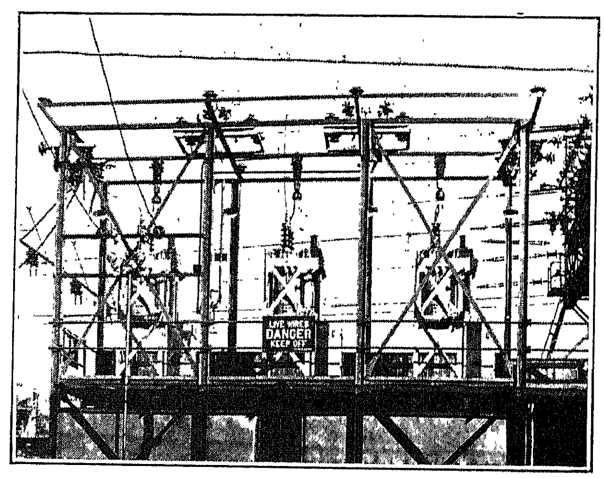

Fig. 3—High-Speed Circuit Breakers, South Norwalk

Communication Line Protection

The method of applying drainage to communication circuits is as follows: The physical circuits are drained by two No. 70-A repeating coils so connected that both primary and secondary windings are in multiple. The midpoints of these windings are then connected to ground through one winding of a No. 122A coil, which acts also as a drain on the phantom circuit. A combination such as this was installed at each end of the branch and at six intermediate points approximately uniformly spaced from each other.

Tests

In the early part of October 1925 a series of tests was made jointly by the American Telephone and Telegraph Company and the New Haven to determine the extent to which the high-speed circuit breakers, as well as the communication line drainage, etc., contributed to satisfactory operation. Oscillograph records of these tests were made, three of which are reproduced here. They are:

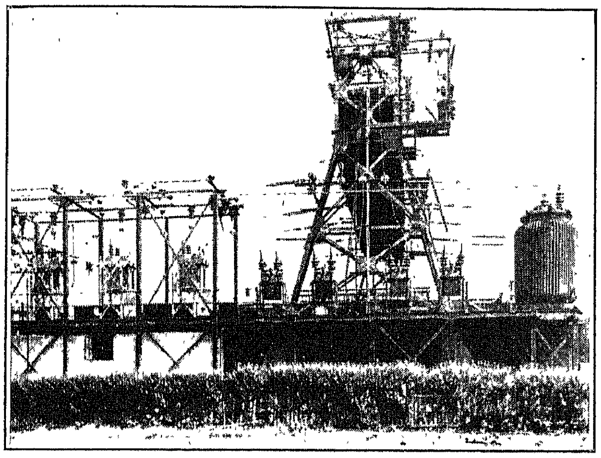

Fig. 4—Substation at South Norwalk

Fig. 5—A short circuit at Danbury, 23.8 mi. from the oscillograph, the latter being at point of supply, South Norwalk. The circuit was opened in one cycle (1/25 sec.) and the current reached a maximum of 1000 amperes.

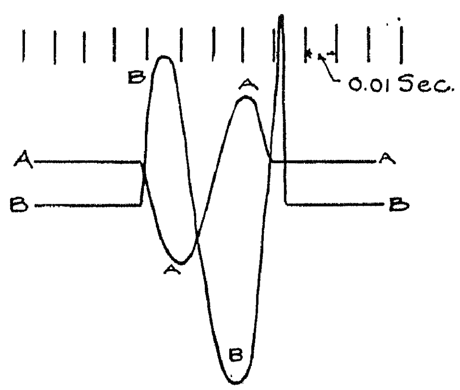

Fig. 5—Short Circuit at Danbury—23.8 Mi.

A. Trolley current—maximum 1000 amperes
B. Volts across drainage at South Norwalk—maximum 48.7 amperes

Fig. 6—A short circuit at Wilton, 7.4 mi. from South Norwalk, showing an opening in one and one-half cycles at a maximum 540 amperes.

Fig. 7—A short circuit at South Norwalk, one-half mile from the oscillograph, showing the circuit open in one-half cycle, the maximum current being 3030 amperes.

Circuit Breaker Operation

Considering the three circuit breakers as a group, it may be noted that since being put in service in July 1925 the operation has been as follows:

Total number of operations on grounds......	717
Ave. number of operations on grounds per circuit breaker..........................	239
Total number of other operations to 1-1-28...	750
Ave. number of other operations per circuit breaker.............................	250

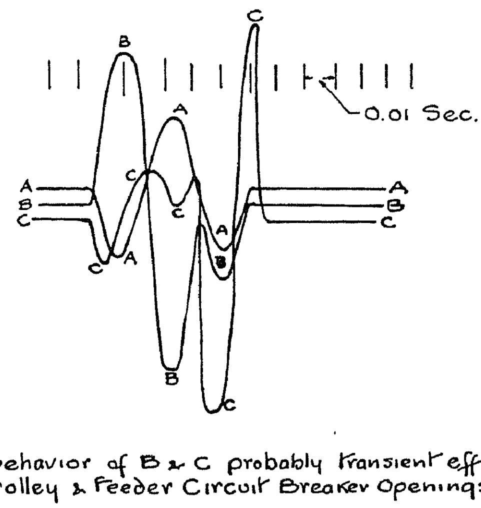

Fig. 6—Short Circuit at Wilton—7.4 Mi.

A. Feeder current—maximum 560 amperes
B. Track current—maximum 685 amperes
C. Induced voltage—maximum 1420 amperes

The circuit breakers have not operated faultlessly and therefore the third, or so-called spare circuit breaker, has been of real use, but this was to be expected. There has been on the circuit breakers as a group, since their installation, a total of 25 operating failures distributed as follows:

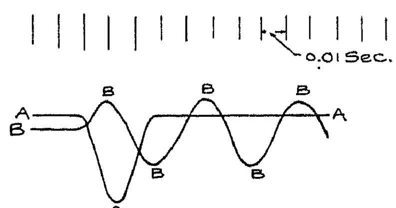

Fig. 7—Short Circuit at Norwalk—0.5 Mi.

A. Trolley current—maximum 3030 amperes
B. Induced voltage, S. N. E. Tel. Co.—maximum 180 amperes.

Trip coils....................	5
Mechanical parts.............	5
Closing motor................	2
Overload relay................	1
Indicating switch.............	2
High-tension terminal.........	1
Unknown....................	9
Total.............	25

Of the above failures those due to mechanical causes have been most difficult to find. Adjustment in length of operating rod had to take into consideration proper sequence of events as between main and auxiliary contacts, along with irregularities on the main contacts due to arcing. If this operating rod length was not correct within fairly close limits the circuit breaker would not close and latch, although it would open satisfactorily. The forged steel spiral-spring ends in the opening mechanism received severe punishment and had to be made heavier. Likewise the foot castings on the legs had to be made of steel instead of cast iron, and the indicating switch operation had to be made somewhat more positive. In general the mechanical difficulties have been reflections of the very high speed of operation, with resultant high starting and stopping stresses.

On the electrical side trip coil failures predominated, due partly to the design of the terminals, and partly to the fact that for some reason the tripping circuit did not open. The tripping current, particularly at 250 volts, is relatively high, and if it is not interrupted as soon as its work is done one can look for trip coil difficulty. The overload relay failure was due to a ground on one of its leads caused by insulation deterioration which in turn was due to heat from adjacent d-c. tripping circuit arc. Barriers have eliminated the possibility of further difficulties due to this source. The motor failures were such as are sometimes found in motors of this nature and involved adjustment of short-circuiting device and cleaning of commutator.

In general, the statement is justified that most of the faults uncovered by our operation would not have appeared if the manufacturer had been given more time to develop the design and test it completely before installation.

Operation of Communication Circuits

It may be of interest to note that the program outlined in paragraph three, parts a, b, and c, has resulted in satisfactory operation to commercial as well as railroad communication circuits.

Acknowledgment

The writer desires to acknowledge kind assistance of Messrs. H. A. Shepard, general superintendent of electric transmission and communication department, S. Withington, electrical engineer, as well as his assistant, H. Brown, and A. R. Belmont, communication engineer.

Discussion

For discussion of this paper see page 1311.

Arrangements of Feeders and Equipment
for Electrified Railways

BY R. B. MORTON[1]
Fellow, A. I. E. E.

***Synopsis.**—This paper outlines the general requirements governing arrangements of distribution system and substation equipment for electrified railways. By way of illustration it presents a general description of the conversion and distribution facilities as recently installed in the electrification of the New York Connecting-Long Island Railroad to Bay Ridge, and in the electrification, now nearing completion, of the Philadelphia-Wilmington and West Chester lines of the Pennsylvania Railroad.*

INTRODUCTION

SUBSTATION equipment necessarily includes conversion apparatus required to translate the power received over transmission lines into suitable form for delivery to the contact system. Such apparatus is usually provided in units so proportioned as to load capacity that the outage of any one unit will not place limitations to the movement of traffic.

Switching equipment must be provided which, in the event of short circuits, will quickly and automatically interrupt the supply of power, and so confine the effect of such interruption as to cause the least practicable disturbance to movement of traffic. Although in practise it is necessary to include switching apparatus of more or less complexity, the ideal switching equipment would be none at all. It is obviously desirable to keep the switching equipment as simple as the nature of traffic requirements will permit.

The several examples of railway electrification, to

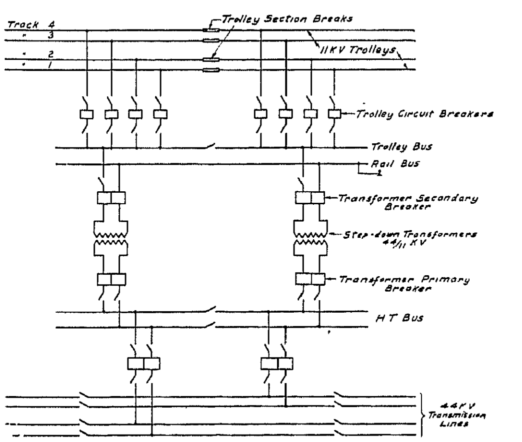

FIG. 1—SCHEMATIC DIAGRAM OF TYPICAL SUBSTATION

Pennsylvania Railroad—Paoli-Chestnut Hill Electrification

which reference is made in this paper, are of a type utilizing the single-phase a-c. system of traction, but some of the features of switching arrangements herein described may also be applied in a d-c. system. Essentially in a d-c. system of traction there must be interposed between the step-down transformers and the trolley bus, suitable rectifying apparatus, such as mercury vapor rectifiers, motor-generators, or rotary converters.

There may be said to be at least four rather distinct methods of arranging the switching equipment in substations, namely:

1. An arrangement which provides for switching,

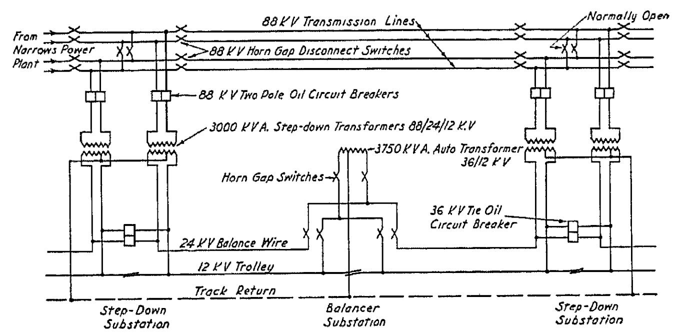

FIG. 2—DIAGRAM OF TYPICAL STEP-DOWN AND BALANCER SUBSTATIONS

Virginian Railway Electrification

under load, the transmission circuits, high and low sides of transformers and trolley feeders, as in the case of the original Paoli-Chestnut Hill electrification of the Pennsylvania Railroad (Fig. 1).

2. An arrangement which provides for switching on the high tension side only for controlling both transmission and trolley circuits, as in the case of the Virginian Railway (Fig. 2).

3. An arrangement which provides for switching, under load, the transmission and trolley feeder circuits, but not the transformers, as in the cases of the original electrification of the Elkhorn Grade on the Norfolk & Western Railway (Fig. 3) and the New York Connecting-Long Island Railroads (Fig. 5).

4. An arrangement which provides for switching under load, on the low tension side only, for controlling both high-tension and low-tension circuits, the transformers being switched and regarded as a part of the transmission system, as in the case of the recent Pennsylvania Railroad Suburban and Through Electrification (Fig. 7).

In the selection of a scheme of distribution for a rail-

1. Project Engineer, Gibbs & Hill, New York, N. Y.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

way electrification, the principal governing factors, not necessarily in the order of their importance, may be listed as follows: source of power; type of system used on any existing electrification to which the new electrification may be joined; maximum concentration of power required for movement of traffic; distances involved, and probabilities of future extension; number of tracks; alinement of railroad and topography of route;

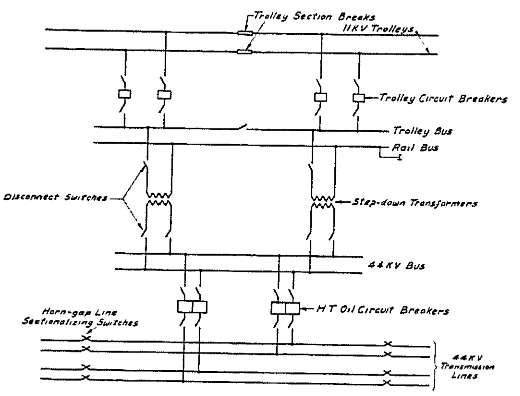

FIG. 3—SCHEMATIC DIAGRAM—MAYBEURY SUBSTATION

Norfolk & Western Railway—Elkhorn Grade Electrification

property available for substation sites; locations of continuously attended points for control; and relative importance of insurance against traffic delays.

An example of simplified substation switching equipment will be noted in the electrification of the Virginian Railway. This system has been described in detail in a paper[2] recently presented before the American Society of Civil Engineers. In a typical substation serving the single track portion of this railroad there are provided three oil circuit breakers. Two of these are high-tension breakers, interposed between the transmission lines and the step-down transformers, while the third is a low-tension breaker, serving to equalize the load on the transformer secondaries, or, in the event of one of the transformers or one of the transmission lines being out of service, serving to feed both trolley sections from one transformer. Fig. 2 shows in diagram the arrangement of power connections.

The balancing wire system of distribution for the Virginian Railway electrification was adopted mainly for the following reasons:

With main substations spaced on an average about 20 mi. apart, it was possible, because of the circuitous alinement of the railway, to shorten materially the over-all length of the transmission line. The saving in cost resulting from this factor, combined with the savings due to simplified switching arrangements in substations, partly offset the higher cost of transformers and the cost of the 24-kv. balancing wire. The advantage of a system which materially reduces the effect of inductive disturbances on paralleling communication wires was therefore secured, but, however, at some expense.

In a railway electrification comprising two or more main running tracks, the contact system is usually sectionalized in such a manner that a power outage on one track will not interfere with traffic movements on the remaining tracks. This necessitates a trolley circuit breaker for each trolley section.

The electrification of the New York Connecting Railroad–Long Island Railroad to Bay Ridge, completed and placed in operation during the summer of 1927, may be taken as illustrative in the arrangement of its feeders and substation equipment. A general description of these features may be of interest.

NEW YORK CONNECTING RAILROAD–LONG ISLAND RAILROAD TO BAY RIDGE

This electrification covers a route 20 mi. in length, extending from a freight terminal yard at Bay Ridge, Brooklyn, to a point of connection with the Harlem River Division of the New York, New Haven & Hartford Railroad at Port Morris, Borough of the Bronx (Fig. 4).

Freight traffic only is handled, with the exception of a

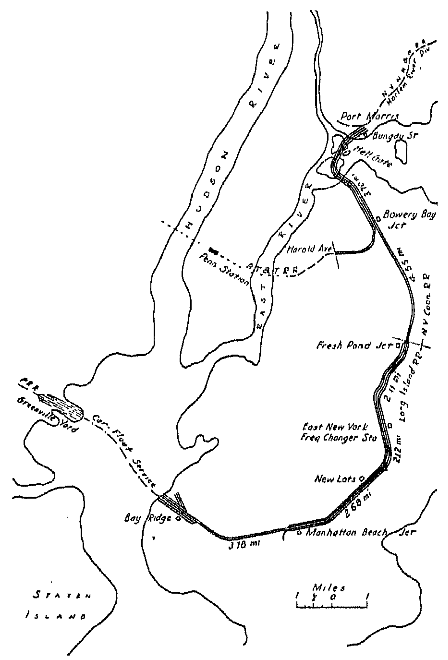

FIG. 4—MAP OF ELECTRIFIED SYSTEM

New York Connecting Railroad—Long Island Railroad—Bay Ridge Improvement

few passenger trains daily over the Hell Gate Bridge route, which service was inaugurated in 1917. Freight movements consist of through freight trains operated by the New Haven Railroad between Bay Ridge and Port Morris, way freight and through freights operated by the Long Island Railroad between Bay Ridge and Fresh Pond Junction, and yard switching at Bay Ridge and New Lots.

Power Supply. The system of electrification is

2. New York, February 1, 1928, by Mr. George Gibbs.

fundamentally an extension of the New Haven electrification, with 11,000-volt trolleys and 11,000-volt feeders of opposite polarity, forming a 22,000-volt, three-wire system. At present, power for operation is received from the New Haven system, which in turn is supplied principally from its own generating station at Cos Cob, approximately 42 mi. from Bay Ridge, and also in part from purchased power delivered to the New Haven at West Farms, Devon, and New Haven.

A variable-ratio frequency changer of 5000 kw. continuous rating at 70 per cent power factor has been provided at East New York, in an addition to one of the substations of the Long Island Railroad. This machine is capable of furnishing the single-phase railway system an emergency supply of power from the 11,000-volt, three-phase, 25 cycle bus, converting the same to power at 11,000 volts, single-phase, 25 cycles, and is also capable of acting as a flexible tie between the two power systems with ability to transfer a desired amount of power in either direction, independently of frequency variations up to a total spread of 6 per cent, equivalent to 1½ cycles. This set is also operated during peak load periods as a synchronous condenser for power-factor correction on the single-phase railway system, for the purpose of improving trolley voltage. When so operated, with the three-phase end of the set electrically disconnected, an automatic voltage regulator so controls excitation as to maintain practically uniform voltage up to a point where the single-phase machine is carrying full rated load of 7000 kv-a. If the system conditions require a loading in excess of 7000 kv-a. to maintain normal voltage, the excitation is so controlled as to automatically droop the voltage, keeping the stator current at an average value corresponding to full load in amperes.

Substations. A total of six auto-transformer stations have been provided, separated by an average interval of 3.8 mi. The locations of these substations, number and size of transformers, and number of trolley and feeder circuit breakers in each are as follows:

Location	Auto-transformers	Trolley breakers	Feeder breakers
Bungay Street	1—3000 kv-a.	5	6
Bowery Bay	1—3000 kv-a.	9	6
Fresh Pond	1—3000 kv-a.	9	6
New Lots ("NO")	1—3000 kv-a.	9	6
Manhattan Beach Jct.	1—3000 kv-a.	7	8
Fourth Ave., Bay Ridge	2—3000 kv-a.	6	4

The transformers are of the outdoor type, self-cooling, and have a turn ratio of 22,000:11,000 volts. The rating as an auto-transformer corresponds to a coil rating of 1500 kv-a. for each half of its winding. The transformers are capable of carrying 150 per cent of rated load for one hour, following continuous rated load, and this followed by 300 per cent of rated load for five minutes.

The transformers are connected to trolley and feeder buses through two-pole, 22,000-volt motor operated horn-gap switches, capable of safely rupturing transformer exciting current.

A schematic diagram of one of the substations, indicating the arrangement of connections of trolleys and feeders is shown in Fig. 5. It will be noted that at this substation, two of the four feeders are tapped and the other two are looped. At the next adjacent substations the order is reversed.

Trolley and feeder oil circuit breakers are of compact design, similar to breakers which are used on the New Haven system. They have a current rupturing capacity of about 3000 amperes at 11,000 volts. Short-circuit currents for trolley or feeder short-circuits adjacent to a substation may reach maximum values considerably in excess of this value. In order to avoid imposing on the circuit breakers of the Bay Ridge system, or on the similar breakers of the New Haven system, a current rupturing duty beyond the interrupt-

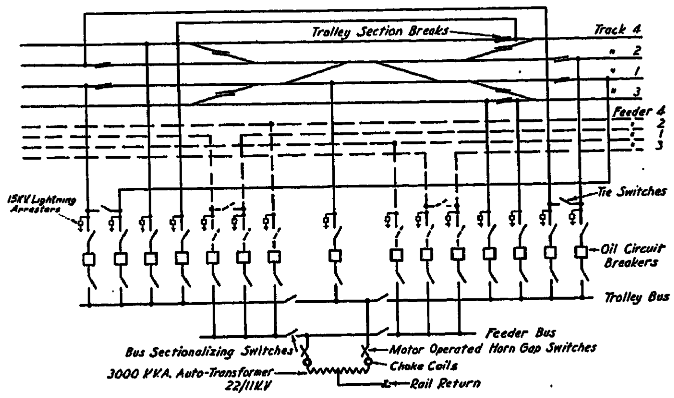

FIG. 5—SCHEMATIC DIAGRAM—"NO" SUBSTATION

New York Connecting Railroad—Long Island Railroad—Bay Ridge Improvement

ing capacity of those breakers, an arrangement of oil circuit breakers is provided on the New Haven system at its Cos Cob power plant and at each other point where purchased power is received, whereby a flow of current of the magnitude of a short circuit causes resistances to be momentarily cut into the trolley and feeder circuits at such supply points. This reduces the flow of short-circuit current to a nominal value. The Bay Ridge breakers have been given a predetermined time delay of one second following the occurrence of a short-circuit, before the tripping circuit is completed, which insures that these breakers shall be required to rupture but a comparatively small current. After slightly more than one second, the several resistances are automatically cut-out and normal voltage is restored to the system.

All auto-transformer substations are unattended. The circuit breakers and motor operated horn-gap switches in each substation are controlled from a panel mounted in a signal interlocking tower nearest to that station. In the case of Bowery Bay substation it was

necessary to utilize a system of supervisory control from Bungay Street tower, a distance of three and a half miles.

Distribution System. The feeder side of the three-wire distribution system comprises four 4/0 copper conductors extending the entire length of the line, as far as Bay Ridge substation. These feeders are carried on pin type insulators of 45,000 volts service rating. Between Fresh Pond and East New York is a four-arch tunnel, 3500 ft. long, in the outside walls of which are banks of cable ducts. Through these ducts four paper insulated, lead sheathed cables of 350,000 cm. are used.

The trolley system for all main running tracks comprises a 4/0 bronze contact wire, 65 per cent conductivity, reinforced by a 4/0 copper auxiliary, supported by a 19-strand messenger ⅝ in. diameter, of high strength bronze. In yard construction the copper auxiliary is omitted.

Track Return. All rail joints on main tracks are single bonded with a No. 1 bond, gas welded to the head of the rail. In yard tracks one rail only is bonded. Cross bonds are installed at intervals along the main line to cross-connect the mid-points of impedance bonds.

The three-wire system of distribution was selected for the New York Connecting Railroad–Long Island Railroad, Bay Ridge line, mainly for the reason that this electrification is fundamentally an extension of the existing electrification of the New York, New Haven & Hartford Railroad. The distances from the sources of power are considerable, but are within the range of economical transmission for the voltage employed. Circuit breakers of relatively low current rupturing capacity are used because they are adequate for the conditions of power supply and because they afford a considerable saving in first cost as compared with breakers of larger current rupturing capacity.

Philadelphia Suburban Electrification of the Pennsylvania Railroad

The electrification of Maryland Division, main line, from Philadelphia to Wilmington, Del., a distance of about 27 mi., and of the Wawa Branch to West Chester, a distance of about 26 mi., is now nearing completion (Fig. 6). Approximately 105 mi. of electrified track are involved in the main line work, and approximately 50 mi. in the Branch.

Substations have initially been equipped for supplying power for the operation of multiple unit trains only, but the Wilmington line has been designed to later form a part of through electrification between New York and Washington, with locomotive operation of main line freight and passenger services.

Power Supply. Power for the electrification is supplied by the Philadelphia Electric Company at 13,200 volts, 25 cycles, single-phase, delivered on the bus bars of the Railroad Company's step-up station at Lamokin Street, Chester. Three self-cooled single-phase transformers of 15,000-kv-a. continuous rating are provided for stepping up this power to a transmission potential of 132,000 volts. This transmission potential was selected by reason of the large amounts of power which will be required for the ultimate through electrification, and the considerable distances to be covered.

Initially two transmission circuits of 4/0 copper are provided, which are supported on the catenary structures. Ultimately it is planned that the number of transmission circuits along the main line may be increased to four.

Substations. A total of nine substations are provided in which the power is stepped down to a trolley potential

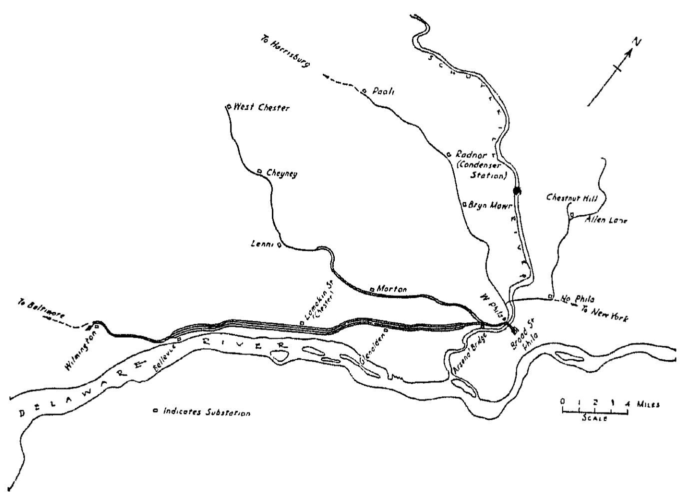

Fig. 6—Map of Philadelphia Suburban Electrification, Pennsylvania Railroad

of about 11,000 volts. The locations of these stations, number and size of step-down transformers and the number of trolley circuit breakers in each are as follows:

Location	Transformers	Trolley breakers
Wilmington	2—4500 kv-a.	4
Bellevue	2—4500 kv-a.	10
Lamokin	2—4500 kv-a.	10
Glenolden	2—4500 kv-a.	8
Arsenal Bridge	2—4500 kv-a.	9
Morton	2—4500 kv-a.	4
Lenni	2—4500 kv-a.	3
Cheyney	1—4500 kv-a.	1
West Chester	2—4500 kv-a.	1

The average interval between substations is 6.4 mi. It is planned that the number of step-down transformers in each of the substations serving the main line may ultimately be increased to four.

The transformers are self-cooling, and are capable of carrying continuous rated load, followed by 150 per cent of rated load for two hours, followed by 300 per cent of rated load for five minutes.

A schematic diagram of one of the substations, indi-

cating the arrangement of connections, is shown on Fig. 7.

A feature of these substations, as well as of the step-up substation, is the absence of oil circuit breakers in the high tension side.

In the step-up substation oil circuit breakers are provided in the low tension side of the transformers, giving automatic protection in the event of transmission line fault. The transformers are connected on the high tension side to outgoing transmission lines through two-pole 132-kv. air sectionalizing switches, remote electrically controlled, which are not to be opened under load, but are capable of interrupting transformer exciting current.

In a similar manner the transformers in each of the step-down substations are connected to the high-tension lines through air sectionalizing switches, and the low tension side of each is connected to trolley and rail buses through a two-pole oil circuit breaker, arranged for automatic tripping on reverse power, on unbalanced

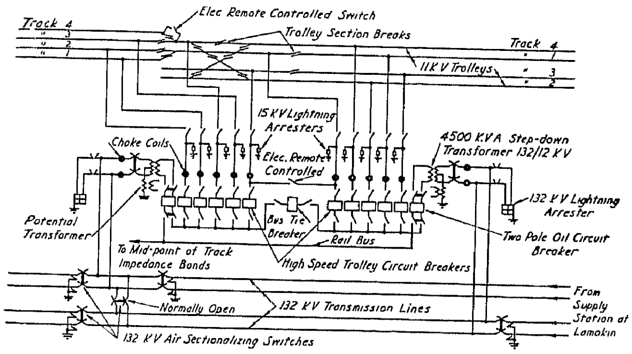

FIG. 7—SCHEMATIC DIAGRAM—BELLEVUE SUBSTATION

Pennsylvania Railroad—Philadelphia Suburban Electrification

voltage on the high tension side, or by differential protection against failure on the trolley bus or within the transformer. A fault on any part of a 132-kv. transmission circuit will trip out of service one transformer in the step-up station and one transformer in each step-down station which is served by the transmission line on which the fault occurs. Such an outage does not affect train operation, as sufficient transformer capacity remains in each substation to handle maximum expected loads. If the transmission line fault is to ground only, and does not involve the opposite conductor, the flow of current through the earth, back to the step-up station is limited to about 200 amperes by a neutral resistance connected to the mid-point of each step-up transformer.

Trolleys are sectionalized at each substation and each trolley section is normally fed from each end, thereby avoiding "stub-end feed." Trolley circuit breakers are designed to open under short circuit within an interval of time not exceeding 1/25 sec. The rupturing capacity of these circuit breakers is 50,000 amperes. This high value of rupturing capacity was required with a view to ultimate conditions as to transformer capacity at step-up and step-down substations. This installation represents the first use on any extensive scale of quick opening circuit breakers in a-c. railway electrification, and it is expected that inductive disturbances and damage to overhead wires and insulators resulting from trolley short circuits will be minimized by the quick acting feature.

At each substation there is provided a small building to house a control storage battery and charging equipment, protective relays and oil conditioning apparatus. All other equipment is of outdoor type.

Substations are unattended, and are controlled from a panel containing control switches and indicating lamps placed in signal interlocking towers or other points continuously attended. Certain substations on the West Chester branch are so remote from a continuously attended tower that it was necessary to provide supervisory control for these substations, utilizing wire circuits in an aerial communication cable along the right-of-way.

Contact System. The contact system for all main running tracks comprises a 4/0 bronze contact wire, 40 per cent conductivity referred to copper, reinforced by a 4/0 copper auxiliary, supported by a 19-strand bronze messenger 5/8 in. diameter, of high strength and relatively low conductivity. No paralleling feeders were required. In yard construction the copper auxiliary is omitted.

Track Return. All rail joints on main track are double bonded, not for conductivity but to minimize signal failure due to broken bonds. A major portion of the trackage is bonded with No. 1 bonds, gas welded to the head of the rail, and on the remainder of the work No. 1/0 bonds with expanded pin terminals are used, installed where possible under the joint plates. Cross bonds of two No. 2/0 copper are installed at intervals to cross-connect the mid-points of impedance bonds.

The type of system of transmission, conversion, and distribution adopted for the Philadelphia-Wilmington electrification gives a high degree of selectivity in the automatic tripping of circuit breakers in the event of short circuits, and is adaptable to future extensions over considerable distances and to such increase in installed capacity as will be required for the future operation of through freight and passenger traffic. The West Chester line was equipped in a manner similar to the Philadelphia-Wilmington line, partly for the sake of uniformity of apparatus, and partly because the 132 kv. transmission lines will ultimately be used as a part of a transmission network, in connection with future extensions of the electrification on the main line to the West, and elsewhere.

Discussion

For discussion of this paper see page 1311.

Protection of Electric Locomotives and Cars to Operate with High-Speed Circuit Breakers

BY E. H. BROWN[1]

Non-member

Synopsis.—This paper discusses the requirements for protecting the high-tension circuits of an electric car or locomotive which operates on the a-c. single-phase system of electrification.

The means which must be employed to secure this protection is outlined. The types of relays used by the Pennsylvania Railroad for this purpose are described, together with the connected control circuits. These relays are known as pantograph lowering relays, and they make use of the opening of the substation breakers on a short circuit to disconnect the electrical equipment of the car or locomotive from the line by lowering the pantograph. Tests of high-speed relays recently developed indicate that these relays will give satisfactory service with high-speed circuit breakers in the trolley feeders at the substations.

In conclusion, results justify the elimination of circuit breakers from electric cars and locomotives by the substitution of the pantograph lowering relay.

THE protection of the electrical equipment of an electric car or locomotive utilizing the a-c. single-phase system may be divided into two general problems:

1. Protection of the high-tension circuits and the transformer from damage due to grounds or short circuits.

2. The protection of the motors and their connecting low-tension circuits.

While the problems are associated, we will, for the purpose of this paper, consider only the problem involved in protecting the transformer and high-tension circuits from the results of short circuits, as transformer overload due to the operation of the motors will be taken care of by the operation of the overload devices in the motor circuits.

It was formerly the general practise, and this practise is still followed on many railroads using the single-phase system, to protect the transformer and the high-tension wiring by an oil circuit breaker of adequate capacity installed on the car or locomotive. On the Pennsylvania railroad, however, a somewhat different practise has been developed for the a-c. multiple unit car and locomotive equipment, as it has been found difficult to provide, in the space available on the cars or locomotives, an oil switch of a capacity adequate to open the high currents which are possible upon short circuit under our operating conditions. This practise is, in brief, to insert, between the pantograph and the transformer, a device known as a pantograph lowering relay, which makes use of the substation circuit breakers feeding the trolley wire instead of an oil circuit breaker on the locomotive or car. The method followed in the apparatus used is as given below:

In the circuit between the pantograph and the transformer is inserted a relay known as the pantograph lowering relay. When an excessive current passes through this circuit, the pantograph lowering relay initiates the operation of lowering the pantograph through the control circuits and electropneumatic operating devices. This operation cannot be completed until the opening of the substation breaker. The consequent removal of current from the pantograph and its connected circuit permits the relay to complete its operation which closes the control circuit to the pantograph lowering device and lowers the pantograph during the time that the substation breaker is out. It can readily be seen that this device must accomplish three things:

1. It must initiate the lowering operation prior to the opening of the substation breaker, because it depends on the excessive current flowing in the circuit to do so.

2. It must not complete this operation until after the substation breaker has opened, as it would be highly undesirable to attempt to interrupt the current flow by lowering the pantograph with the resultant possibility of severing the overhead contact wire by a power arc.

3. It must lower the pantograph in the interval between the time of opening of the substation breaker and the closing of this breaker by the substation operator.

Other features of the device are important and these will be dealt with in the following paragraphs:

It may readily be seen that after the device has functioned to lower the pantograph on a car or locomotive upon which the equipment is defective, the pantograph should not be raised by the ordinary means at the motorman's command. An interlocking must be provided at the pantograph lowering relay to prevent raising of the pantograph by the usual control methods.

It is also necessary that the pantograph lowering relay shall assure, as far as possible, that the pantograph on the car or locomotive, upon which the equipment is defective, shall remain lowered even though the latching device may fail and consequently means should be provided to retain the air in the lowering cylinders, thus preventing raising of the pantograph, even should the locking device fail.

The principal requirements will now be considered in detail, to point out the manner in which each affects the design of the relay. The first requirement, that the

1. Elec. Engg. Dept., Pennsylvania Railroad, Altoona, Pa.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

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relay initiate the lowering operation before the substation breaker opens, is by far the most important. It is fundamental and upon the success of this first operation depends the whole sequence of the further events. When the use of the high-speed substation breaker was decided upon for the Philadelphia-to-Wilmington and the West Chester electrifications of the Pennsylvania Railroad, preliminary laboratory experiments demonstrated that the type of pantograph lowering relay which had previously been used would not operate with this type of breaker. While these relays had been satisfactory with the lower speed of operation of breakers in the existing substations, the high-speed breaker opening the short circuit as rapidly as one-half a normal cycle on 25-cycle current, would not permit a sufficient impulse to be received by the relay before power was off the line. It therefore became necessary to develop new relays requiring less energy input, but operating on the same current values

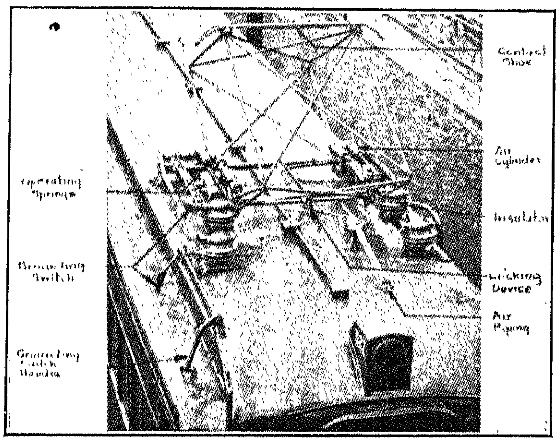


FIG. 1—MULTIPLE UNIT CAR PANTOGRAPH

as before. These newly developed types will shortly be described.

The second requirement for the relay is that it must not complete the operation of lowering the pantograph until the substation breaker is opened. This is an important function, but one which, with quick acting breakers especially, will seldom be called into effect. There is one condition, however, which makes this requirement most important. This condition exists when a short circuit occurs of sufficient value to trip the pantograph lowering relay, but does not operate the substation breaker immediately. The pantograph in this case must not be lowered until the short circuit has reached a sufficient value to trip the substation breaker and remove power from the line. This function can be accomplished by means of an electrical interlock breaking the pantograph lowering circuit as long as the relay is energized by the short circuit current.

The third requirement is that the relay must lower the pantograph before the substation breaker is reclosed. This is not difficult to meet. Under usual operating conditions, when a substation breaker opens upon short circuit, approximately one minute will elapse before the substation operator has received instructions from the qualified supervisor and has reclosed the breaker. Since lowering the pantograph requires a time of only about one second, this can readily be accomplished.

The lowering operation, nevertheless, must be an automatic function of the relay and must be performed without unnecessary delay.

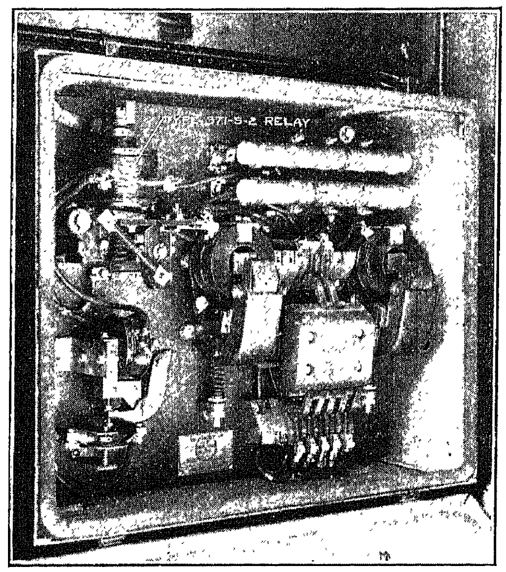


FIG. 2—TYPE 371S2 PANTOGRAPH LOWERING RELAY
Standard type in service on the Philadelphia-Paoli electrification

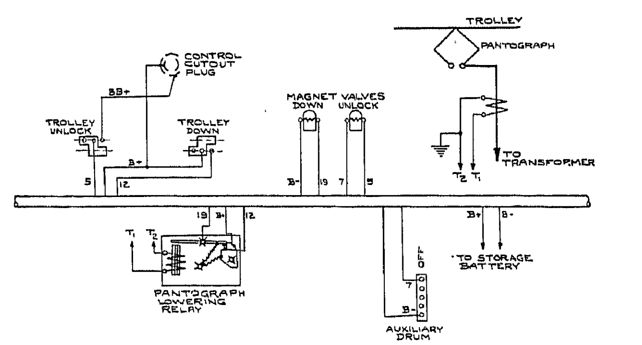


FIG. 3—DIAGRAM OF PANTOGRAPH CONTROL CIRCUITS USING TYPE 371S2 PANTOGRAPH LOWERING RELAY

A description of the various types of relays employed for lowering the pantograph will bring out the means by which the above outlined requirements have been accomplished.

First, we will consider the relay and its connecting circuits now in service on the Philadelphia-to-Paoli electrification of the Pennsylvania Railroad. This relay is known as "Type 371S2." Fig. 3 illustrates diagrammatically the electrical control affecting this relay and the pantograph. The pantograph is in its normal operating position. The auxiliary, or sequence drum, by which the motor switches are controlled, is in the "off" position, indicating that the motor switches

are open. The pantograph may now be lowered by pressing the trolley "down" button, admitting air to the lowering cylinders on the pantograph. It will be noted, however, that by means of the 12 and 19 wires, this operation is so interlocked that it cannot be performed when the circuit has been opened by energizing the pantograph lowering relay. This gives the necessary protection to prevent the pantograph from being lowered during a short circuit. When the pantograph has been lowered, it is automatically latched by a

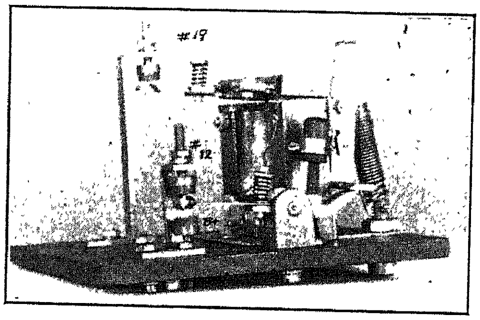


FIG. 4—TYPE UC-8 PANTOGRAPH LOWERING RELAY

mechanical device. It can be unlatched by pressing the trolley "unlock" button. The operating springs will then raise it to the contact wire. This operation is interlocked electrically in two places. First, the control cut-out plug must be placed in its proper receptacle by the motorman, and second, the auxiliary drum must be in its "off" position, so that the motors are disconnected.

These are the normal operating conditions. We now come to the operation of the pantograph lowering relay. When the current transformer shown on Fig. 3 is energized by an excess current flow in the high tension lead to the main power transformer, it energizes, in turn, the operating coil of the pantograph lowering relay. The armature of the relay is drawn up and parts the circuit between the motorman's trolley "down" button and the "down" magnet valve, so that the motorman cannot lower the pantograph and the circuit is held open for the duration of the short circuit. As soon as power goes off the trolley, by opening of the substation breaker, the operating coil of the relay is deenergized. In the meantime, the contact bearing member has been rotated by means of a spring, so that, when the armature falls back, it closes the circuit to the battery and applies current to the "down" magnet valve, thus lowering the pantograph. This supplies the automatic lowering operation of requirement No. 3, before mentioned.

When the "down" magnet valve has been energized by operation of the pantograph lowering relay, it is connected directly to the battery and remains energized. Thus air pressure is held in the pantograph lowering cylinders as long as it is available in the control air reservoirs. By this means the trolley is held down, regardless of the failure of the latching device and also regardless of an effort to raise it with the motorman's "unlock" button.

Resetting of a relay by members of the train crew is not permitted. A car on which the pantograph has been lowered by the operation of this relay, and which does not respond to the "unlock" button, is towed by the other cars in the train until such time as it can be inspected by members of the shop force, in order to determine the cause of the lowering operation.

Relays, as above described, using an electromagnet operated by current from a current transformer in the main high-tension lead and having a movable iron armature, have been in satisfactory operation up to the present time, but have proved unsatisfactory for use with high-speed breakers. A new design of this same type has recently been produced that has not yet demonstrated its ability to operate at the required speed.

To take the place of these relays, two different types have been submitted. One is operated directly by the magnetic effect of the power current passing through a surrounding iron core and eliminating both current transformer and relay operating coil. The other type utilizes current from the current transformer to operate a solenoid and plunger instead of the electromagnet and armature. Both of these devices have demonstrated, by means of oscillograph tests, that they will perform satisfactorily with short circuit current flowing in the trolley circuit for less than one-half cycle.

Reference to Fig. 5 will show the circuit arrangement for the first of these high-speed relays. This relay is known as "Type UC-8." It is composed of a rectangular magnetic core surrounding the high-tension lead,

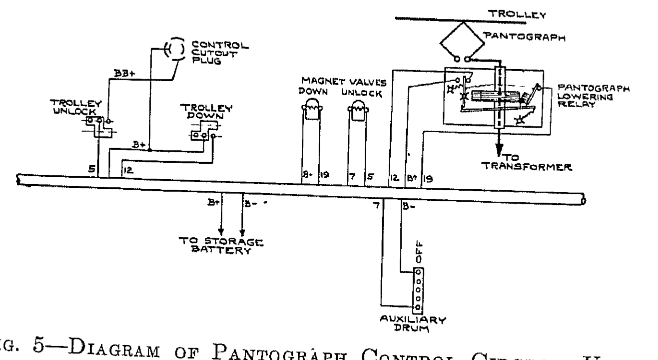
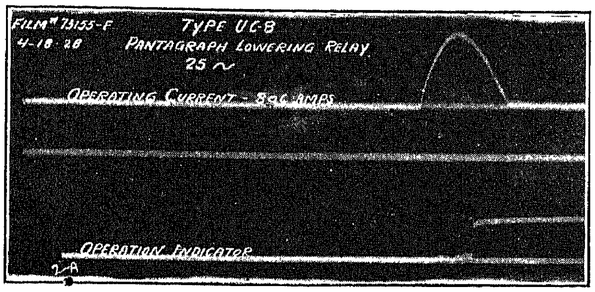


FIG. 5—DIAGRAM OF PANTOGRAPH CONTROL CIRCUITS USING TYPE UC-8 PANTOGRAPH LOWERING RELAY

one leg of which core is pivoted along its length (see Fig. 4). This leg is slightly tilted under normal conditions to give a small air-gap. Current flow in the high-tension cable magnetizes the core, tending to close the air-gap. By means of contacts mounted on the movable leg, the same circuit relations are obtained with this relay as with the old type of relay. By the use of a laminated magnetic circuit and moving parts of low moment of inertia, it has been possible to design this relay to operate within approximately

one-third of a cycle. A typical oscillogram of this relay is shown in Fig. 6.

The second type of high-speed relay is shown in Fig. 7. It is operated by means of a solenoid plunger and is shown in conjunction with a different type of pantograph control, utilizing only one magnet valve (see Fig. 8). The magnet valve admits air to a cylinder at the pantograph, the piston of which cylinder opposes the action of holding-down springs and permits the operating springs to raise the pantograph. When air is released from the cylinder by deenergizing the magnet valve, the holding-down springs lower the pantograph. These springs are so interlinked that they overcome the raising action of the operating springs and hold down the pantograph without the necessity of an additional latching device.



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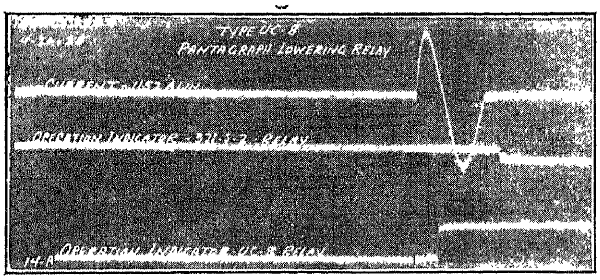

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Fig. 6—Typical Oscillograms of Type UC-8 and Type 371S2 Relays

a. The upper line indicates trolley current. Note that the current was flowing during only one half a cycle

The middle line traces a circuit indicating the operation of a type 371S2 relay. The fact that this line is unbroken indicates that the relay did not function

The lower line is traced by a circuit through the contacts of a type UC-8 relay. The relay has operated well within the one-half cycle

b. The current flow lasted for a full cycle in this test

The type 371S2 relay received sufficient impulse this time to operate. The contacts of the relay, however, did not part until after power was off the trolley

The type UC-8 relay again operated within one half cycle

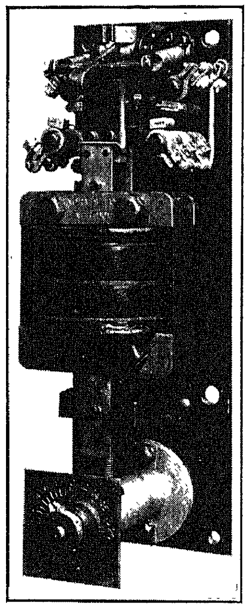

Fig. 7—Solenoid Type of Pantograph Lowering Relay

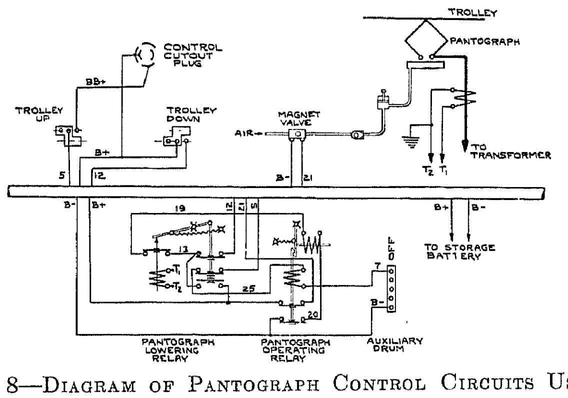

Fig. 8—Diagram of Pantograph Control Circuits Using Solenoid Type of Pantograph Lowering Relay

An additional relay is necessary with the type of control just described. This relay is called the pantograph operating relay. The function of this relay is to hold open the magnet valve which maintains the pantograph in its extended position, against the contact wire, during normal operation.

By referring again to Fig. 8 it will be seen that, in order to keep the pantograph in its operating position, the 21 wire leading to the magnet valve must be energized and thus the pantograph operating relay must be in its latched position, as shown by the diagram. This is done by energizing the lower solenoid of the relay by means of the trolley "up" button. This push-button circuit is interlocked, as with the previously described pantograph operating circuit, so that the control cutout plug must be in place and the auxiliary drum must be in the "off" position. It is also interlocked with the pantograph lowering relay, so that the operating relay cannot be energized when the lowering relay has been tripped.

The normal lowering operation is performed by energizing the upper or tripping solenoid of the operating relay which trips the latch and breaks the circuit from the magnet valve wire No. 21 to the battery. Operation of the tripping solenoid is interlocked with the pantograph lowering relay, so that when the solenoid of this latter named relay is energized the circuit to the

tripping coil is broken and is not closed until the pantograph lowering relay is deenergized and the 19 wire is reconnected to the 13 wire. It can be seen that, when the lowering relay is tripped, this 13 wire is

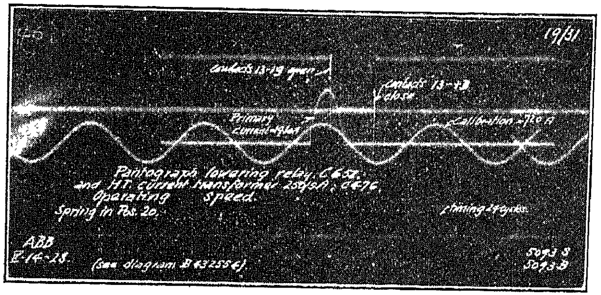

Fig. 9—Typical Oscillogram of Solenoid Type of Pantograph Lowering Relay

This type of relay has given satisfactory test results with currents from 500 amperes upward flowing for one half cycle

This oscillogram indicates successful operation with 1930 amperes flowing for 0.3 cycles on the basis of 25 cycles per sec.

connected directly to the battery and trips the operating relay immediately upon removal of short circuit current from the trolley by the substation breaker. An oscillogram showing a typical operation of this relay is given in Fig. 9.

In conclusion, results secured in the past with pantograph lowering relays have been satisfactory. There have been no indications that the relays have failed to function when required. Although in numerous instances the relays have operated without proper cause, these false operations have been largely eliminated by improved design and proper setting of the relay. Recently, types have been developed which are more positive in action and are less susceptible to vibration, and they have been made sufficiently sensitive and rapid in operation to be used with high-speed substation breakers.

It is felt that the additional investment required and the effort necessary to provide space on locomotives and cars for circuit breakers of proper size is unwarranted, and that such breakers may be eliminated by the installation of a pantograph lowering relay making use of the opening of the substation breaker to disconnect the electrical equipment of the car or locomotive from the line by lowering the pantograph.

Discussion

For discussion of this paper see page 1311.

The High-Speed Circuit Breaker in Service
on the Illinois Central Railroad

BY W. P. MONROE[1] and R. M. ALLEN[2]
Member, A. I. E. E. Non-member

Synopsis.—The purpose of this paper is to describe briefly the distribution system of the Illinois Central Suburban Electrification and to state considerations influencing the selection of high-speed circuit breakers for d-c. feeder and machine protection. The knowledge gained by nearly two years' operating experience with this system, which contains 98 high-speed circuit breakers, and the conclusions reached, are also presented.

* * * * *

THE first large installation of high-voltage d-c. high-speed circuit breakers for railway service was placed in operation on the Chicago suburban electrification of the Illinois Central Railroad, in July, 1926. The reasons for the adoption of these circuit breakers for this electrification, and the results thus far obtained with them, may be of interest to those who are contemplating similar applications. With this idea in mind, the distribution system in general will first be described with special regard to those features influencing the selection of the high-speed breakers. A description of the installation and tests will then be given, and finally, the operating experience of twenty months service will be discussed.

DESIGN FEATURES OF DISTRIBUTION SYSTEM[3]

The distribution system of this 1500-volt d-c. suburban electrification was designed to deliver current to the trains with the necessary voltage regulation, with economy in the use of copper, and with the utmost reliability. A simple system resulted consisting of seven substations conveniently spaced and feeding directly a catenary system without additional feeders paralleling the tracks. A satisfactory efficiency of distribution was obtained by the use of *tie stations* to connect the catenaries of all tracks together at various points, thus dividing the current among the catenaries over all tracks and utilizing the total copper to the best advantage.

The absence of feeders, other than the catenaries themselves and the substation connections thereto, is a factor in obtaining simplicity and in applying high-speed circuit breakers. It happened that the mechanical design of the catenary was very well suited to the conductivity requirements, this feature being partly due to the use of tie stations and partly due to the fairly close spacing of the substations.

The tie stations, besides increasing the distribution efficiency, divide the catenary system into short sections, each fed through its own circuit breakers. Because of the large number of sections and sectionalizing points of this design, remote control of the circuit breakers is necessary. The Illinois Central system makes use of supervisory control by which the power supervisor, from his desk, can open or close any circuit breaker on the system and receive indications of the opened or closed positions of these breakers at any time.

A simplified schematic diagram of the distribution system in the district having the heaviest traffic is shown in Fig. 1. It is of that portion of the system extending from the north terminus at Randolph Street to Brookdale Substation, 8.3 miles south. On every

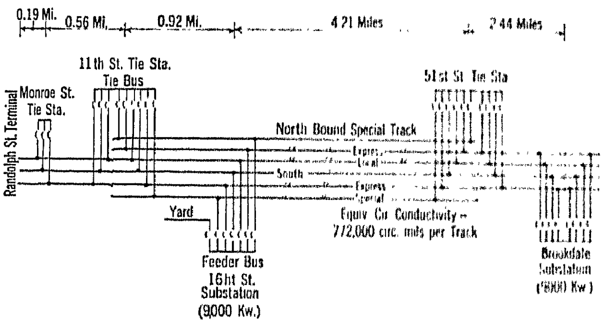

FIG. 1—SCHEMATIC DIAGRAM OF PORTION OF DISTRIBUTION SYSTEM

week-day over 560 electric trains pass through this district, the trains ranging from two to eight cars in length, the average car weighing 63 tons. The load factor, or ratio of average hour to maximum hour over 24 hr., is approximately 40 per cent for a typical week-day load.

The complete distribution system is shown in Fig. 2.

CONSIDERATIONS LEADING TO THE SELECTION OF HIGH-SPEED BREAKERS FOR THE SERVICE

The reliability of the distribution system depends upon adequate protection from short circuits, overloads, and other electrical disturbances. Its availability, or freedom from service interruptions, depends upon the quick isolation from the rest of the system of a section directly affected by the fault without interfering with service on the neighboring sections.

An inspection of Fig. 1 shows that in the Illinois

1. Assistant Engineer, Illinois Central Railroad.
2. Power Supervisor, Illinois Central Railroad.
3. For a detailed description of the I. C. R. R. distribution system and other phases of this electrification, see series of articles in *General Electric Review*, April, 1927.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Central distribution system most of the sections of track are fed directly or indirectly through a large number of circuit breakers; and that if a short circuit occurs in one section, a number of other sections may be affected unless only the breakers feeding directly into the short circuited section open and isolate it. The circuit breakers, therefore, should have a high degree of selectivity in their operation.

They should also act at sufficiently high-speed to avoid serious burning of the catenary or train equipment.

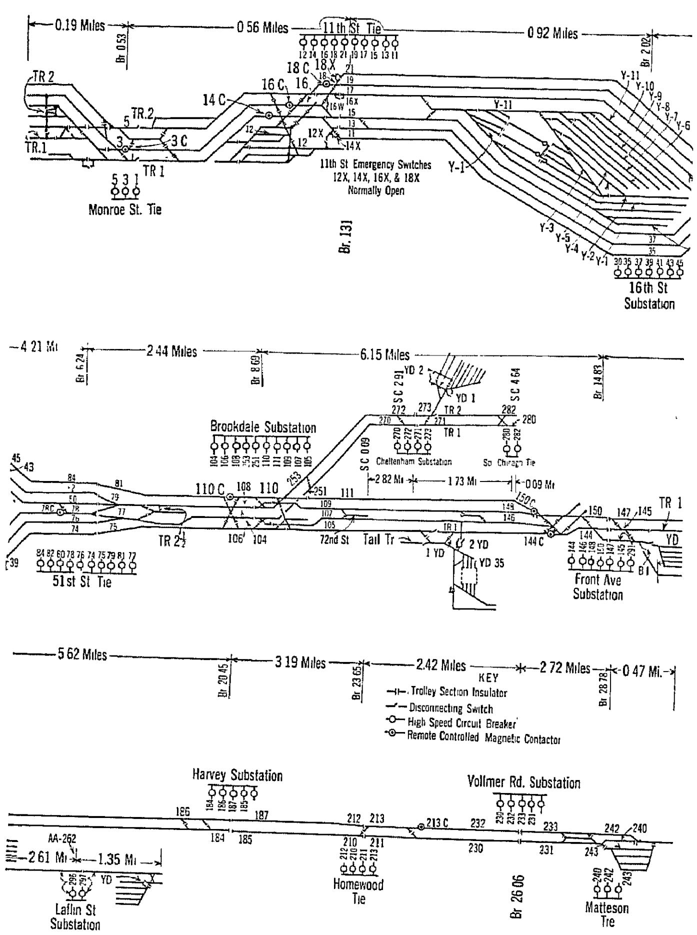

Fig. 2—Complete Scheme of Distribution on the Illinois Central Railroad

They should be adapted to remote control since many of them will be in unattended stations and all must be under direct control of the power supervisor's office.

Their reliability should be such that they will not require very frequent maintenance attention.

The Commonwealth Edison Company of Chicago and affiliated Public Service Company of Northern Illinois own and operate the substations feeding the Illinois Central distribution system, and also own and maintain the feeder circuit breakers in the substations. The operation of these breakers, however, is of great importance to the railroad because they form a part of the distribution system and must act in conjunction with the tie station breakers. The Edison Company and railroad engineers, therefore, worked together in selecting the type of circuit breaker and protection scheme used in the substations.

A study of the merits of all proposed 1500-volt d-c. circuit breakers, including extensive factory tests, resulted in the selection of the General Electric type J R high-speed circuit breaker for the service, and this type is used in all section feeders at all substations and tie stations (Fig. 3). They are also used in both positive and negative leads of the synchronous converters in substations. The detailed theory of action of this breaker has been previously described before the Institute.[4]

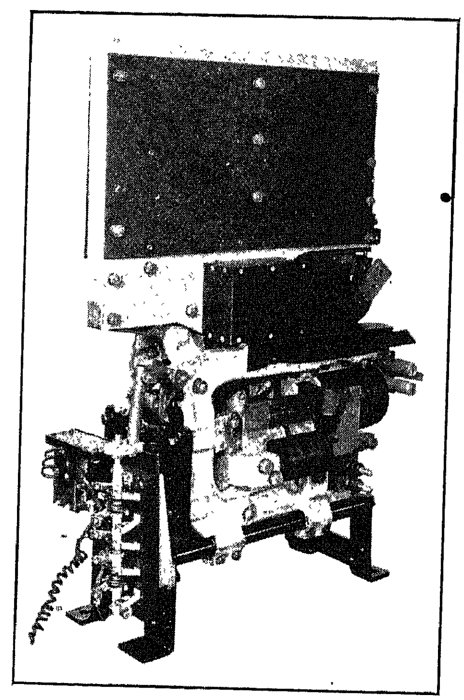

Fig. 3—High-Speed Breaker Unmounted

Installation and Inauguration of Service

The most modern type of construction was used in the installation of the circuit breakers in both substations and tie stations. Each high-speed breaker is mounted on its own truck with control panel, and spare trucks with breakers are available so that repairing is made easy by the removal of the bad order circuit breaker and truck to be repaired and replacing it with a spare truck containing a spare circuit breaker. The circuit breaker trucks can be interchanged readily in the tie stations and in the substations, but an attempt is made always to keep each breaker in the same feeder. Although most of the parts are interchangeable, a complete tie station breaker cannot be interchanged with a substation breaker, because the holding coil of the tie

4. *The High-Speed Circuit Breaker in Railway Feeder Networks*, by J. W. McNairy, Trans. A. I. E. E., Vol. XLV, 1926, p. 962.

station breaker is energized from 1500 volts while that of the substation breaker is energized from the substation 125-volt d-c. supply.

Automatic reclosing features are a part of the control of the tie station breakers, but the closing of substation feeder breakers is governed entirely by supervisory control. Both tie stations and substations are equipped with transfer buses so that in emergencies two or more sections can be fed through the same circuit breaker.

The calibration of the feeder circuit breakers was made at the factory. The settings of the tripping points, however, were precalculated by the railroad company's engineers, and the breakers were set accordingly during the installation. In order to make sure that the predetermined settings were right, a number of short circuit tests was made at the completion of the installation and when power was available at the d-c. buses of the substations. A test car was equipped so that short circuits could be applied at any point, and an oscillograph was installed in the car to record the short-circuit currents and time characteristics of the circuit breakers.

The first tests were made at the Homewood tie station, in an outlying district, where short circuits were applied to the catenary at a point very close to the tie station. It was found that the selectivity of the circuit breakers in isolating the fault was very satisfactory. Tests were also made at 11th Street tie station, one of the largest tie stations in the system, and in this case also the selectivity was satisfactory with the predetermined settings, but some minor adjustments were found to be necessary. Similar tests were made at the other tie stations and substations. In this way the system was "tuned up" for safe and correct operation of circuit breakers. In only a few cases was it deemed advisable to change the predetermined circuit breaker settings.

In the two-track district between Front Avenue and Harvey substations, there is no tie station, (see Fig. 2). It was found that the rate of current rise at one of the Front Avenue substation feeder breakers was not sufficient to open it when a short circuit was applied near the Harvey substation, although the Harvey substation end cleared satisfactorily. The short-circuit current in this case is limited to a maximum value of approximately 3500 amperes by the resistance of the line. The predetermined setting of the Front Avenue breakers was 4000 amperes, but it had to be reduced to 3500 amperes to insure protection. Since the breakers feeding the district south from Brookdale substation to Front Avenue substation, and those feeding north from Harvey substation to Front Avenue have the same feeding distance without tie stations, their settings were also lowered to 3500 amperes. Later, the manufacturers altered the design of the inductive shunt for these breakers, changing both resistance and inductance, so that the settings could be raised to 4000 amperes with ample protection. These circuit breakers with low settings are now all equipped with the new shunts and the settings readjusted to 4000 amperes accordingly. Since the accelerating current of a ten-car multiple unit train approaches 4000 amperes the setting at 4000 amperes (for straight overload) seems to be low to prevent circuit breaker openings from the useful load. Actually, the breakers are sometimes opened by the load, and as traffic increases, the openings will increase. It has always been the intention of the railroad to build a tie station in each of these districts when the traffic so demands.

These preliminary tests on the distribution system have proved the advisability, if not the necessity, of thoroughly trying out a distribution system of this kind before regular service is started. As a further precaution, when the I. C. R. R. electric suburban service was fully inaugurated in August, 1926, emergency operators were stationed in the most important tie stations during the rush hours to take care of any failure or faulty operation of the circuit breakers. The necessity for this latter precaution was not proved, however, since no serious troubles developed.

Results of Twenty Months Operating Experience

Since August 1926, the high-speed breakers have been in continuous service handling the dense traffic of the Illinois Central electrified suburban lines. During this period, there has been opportunity to observe their performance under varying conditions, and there are presented herewith brief comments on certain features of the actual operation in service of these high-speed breakers.

Advantages

The inductive shunt principle and directional characteristics of the high-speed circuit breakers make automatic isolation of trouble by selective operation simple and almost 100 per cent.

The high-speed operation reduces to a minimum the damage to train equipment and overhead. In fact, the burning is so slight that in most cases it is difficult to locate by inspection a traction motor which has flashed over. In no case has the damage by a single flashover been sufficient to necessitate taking a motor out of service.

With a lapping section insulator, such as is used on the Illinois Central, more or less burning is caused by a pantograph moving over a section insulator, one side of which is alive and the other side temporarily grounded by a short circuit or for some other reason. High-speed circuit breakers reduce this burning to a minimum. A recent communication from the Victorian Railways of Melbourne, Australia, which is in the process of changing to high-speed circuit breakers on their 1500-volt d-c. electrification, states that trouble from this cause has been considerably reduced thereby. Their report bears out the experience of the Illinois Central.

Care of the high-speed circuit breaker contacts has

been found to be almost unnecessary, due to the secure manner in which they are held together magnetically, instead of relying on a spring and latch arrangement.

In the early stages of electric operation, there was a very large number of automatic circuit breaker openings for which there was no visible cause. Many of these were due to overhead or train equipment troubles which occurred periodically and the small amount of burning made it impossible to locate the fault by ordinary inspection. Others were known to be due to motor flashovers caused by wheels slipping on wet rails; this is now avoided by proper handling of the trains by motormen.

To trace recurring troubles, a systematic record of automatic circuit breaker openings is kept. For each automatic opening a notation is made in this record of the train in the trolley section, the numbers of the motor cars in the train, location of the train, and the name of the motorman. The following results were and are obtained from the study of periodic summaries of this information:

1. Motor flashovers due to slipping of wheels was confined to a few motormen. These motormen were given special instructions and motor flashovers from this cause have been reduced from about thirty per month to about three per month, and the damage is almost negligible.

2. If an unusual number of circuit breaker openings is found to occur at times when trains are passing a certain point, a thorough inspection of the overhead is made, which usually results in the discovery of a catenary defect at the location.

3. Car equipment trouble is shown by an excess of circuit breaker openings marked against a particular car and this car is taken in for inspection. These inspections invariably verify the evidence shown by the automatic opening report.

It is believed the tracing of these faults before serious damage results is made possible by the high speed characteristics of the circuit breakers.

Disadvantages

There is theoretically an inherent defect in the high-speed breaker characteristics as applied in this service with a short circuit occurring at the time of heavy traction load. When the circuit breaker is carrying heavy current in the right direction for its operation and a short circuit occurs on an adjacent section not directly fed by the breaker, there is a possibility of the breaker opening automatically and incorrectly from the selectivity standpoint. This incorrect operation is due to the load current superimposed on the short-circuit current, the effect being to lower the critical rate of current increase which will open the breaker on short circuit. Actually there have been very few incorrect automatic openings of circuit breakers which have been traced to this cause.

The setting of high-speed circuit breakers on the Illinois Central is accomplished by turning a one-inch iron screw in or out of the holding coil core, thus varying the reluctance of the holding coil magnetic circuit. A marked brass calibrating plate serves as a scale. Such a method of setting is not very accurate considering that highly selective operation is expected. Also, a circuit breaker truck must be removed from the circuit in order to change the setting.

The breaker setting is changed somewhat by the wearing of the main contacts, and periodic calibrating will probably be necessary. Such calibration would require artificial loading which would be cumbersome with 5000- or 6000-ampere settings. However, this will be an infrequent procedure.

Although its advisability may be questioned, it is a practise of most operating companies to relieve traffic congestions by holding carbon circuit breakers closed for a short time. The high-speed circuit breaker does not permit this practise and three cases of breakers opening on legitimate load on the Illinois Central have resulted in serious delays.

It is sometimes desirable to burn clear a minor short circuit. This is almost impossible due to the high-speed operation. In one case, a No. 12 A. W. G. meter lead grounded to the meter frame and could not be burned clear. This occurred on a test train previous to regular operation, but could have caused serious delays had it occurred in regular service, since it was difficult to locate.

The injurious effects of the high-voltage surges induced by the high-speed operation have sometimes been cited as a disadvantage of the device. These surges on our system amount to approximately double the line voltage and are greater than the surges due to openings of carbon circuit breakers. There has been no direct evidence of damage caused by these surges on the Illinois Central.

A number of minor changes in design of the high-speed breakers has been effected since the original installation. These alterations were made by the manufacturers to correct faults which developed under operating conditions. As an example, considerable trouble was experienced by the breakers pumping, due apparently to bouncing of the armature against the core. This pumping often resulted in the reset coil burning out. A change in design of the reset coil core has corrected this defect.

The reset coils of the present high-speed breakers seem to be designed with only a narrow margin of safety as regards operating temperature, since they will reach dangerous temperatures if operated at too frequent intervals. A more liberal design of coil would correct this disadvantage.

Two serious substation bus short circuits were experienced, which may have been due to insufficient clearance of the sheet metal enclosure of the breaker mechanism. The circuit breakers are now being mounted on an ebony asbestos base, instead of metal,

and no further trouble is expected. It is understood the manufacturer is incorporating this change of design in all new high-speed circuit breakers.

It was necessary to raise the overload setting and to remove all but ⅜ in. of the iron on the inductive shunt of the positive machine breaker in the substations, which was set for a low value of reverse current. A sudden interruption of current in the normal direction (such as opening of a feeder breaker) causes a reverse flow of current in the bucking bar due to the collapse of magnetic flux in the inductive shunt, the effect being to open the breaker unnecessarily. The changes in the setting and inductance of the shunt obviate this difficulty.

It is concluded that the disadvantages in this case may be said to be minor defects and there is no doubt that the high speed breaker has contributed much to the success of the Illinois Central electrification.

Discussion

PAPERS ON ELECTRIFIED RAILWAYS

(McNairy, Wilcox, Bardo, Morton, Brown, Monroe and Allen)

Denver, Colo., June 27, 1928

H. C. Graves: Mr. Wilcox mentions selective relaying equipment as a necessary adjunct to the breaker described in the paper presented by him. I should like to outline the system conditions obtaining on an actual, typical system, which made simple over-current tripping means inadequate, to describe the application of high-speed relays, and to give test results which illustrate the adequacy of the protective relay equipment used.

The four-track railway system connection is shown at the bottom of the accompanying Fig. 1. The four 11-kv. contact lines are sectionalized at each feed-in substation, which are located at approximately equal intervals. Each 11-kv. substation bus is fed by high-tension feeders through one to four transformers depending on load conditions. The generating capacity feeding into the high-tension feeders through transformers, may vary from one to eight generators. The impedance of the high-tension feeders is negligible as compared to the impedance of generators, transformers, and contact lines.

Short-circuit conditions existing on this system are as shown at the top of Fig. 1. Since the high-speed relays must operate within 0.01 sec., or ¼ of the cycle, after the relay setting is exceeded, they must frequently operate under asymmetrical current conditions. For this reason, the maximum current condition which must be considered is the maximum instantaneous asymmetrical condition. These maximum values of current which operate the relay on the faulty line, for example at bus A in Fig. 1, are shown in Curve 1 ranging from 24,000 amperes with a fault located just outside of the breaker near the bus to 2700 amperes when the fault is at the opposite end of the line. Minimum values of fault currents will exist when the fault occurs at a time which causes symmetrical conditions of current to exist, and when the generating capacity is a minimum. These currents are as shown by Curve 2. The ratio between maximum fault currents to minimum currents with all breakers closed is seen to be approximately 6 to 1.

During fault conditions, some currents will flow in unfaulted contact lines and tend to cause operation of their protective relays. Curve 3 shows how these currents vary for a particular operating setup. Under these conditions the line relays must not cause tripping.

Using these curves as a basis for determining the type and setting of protective relays it may be seen that instantaneous over-current relays cannot be applied to protect against all conditions because: (1) Under minimum operating conditions they must clear with 1700 amperes flowing into each end of the line, the fault being in the middle; or if the fault occurs at one end of the line the breakers must clear with 4200 amperes flowing at that end but only 600 amperes flowing at the other end. This is shown in Curve 2. (2) Under certain conditions, as shown in Curve 3, 2700 amperes may flow in the unfaulted line which must not cause clearing. If the relays do operate under this condition, a total of 16 breakers may open, two of these alone being sufficient to clear the faulty line. (3) To the fault current in the unfaulted line may be added load current of 1200 amperes which still must not cause clearing.

Thus the relay system must operate with only 600 amperes flowing in a faulted line and must not operate with 3900 amperes flowing in an unfaulted line in order to assure perfect selectivity. Further calculations also show that with a fault near one end

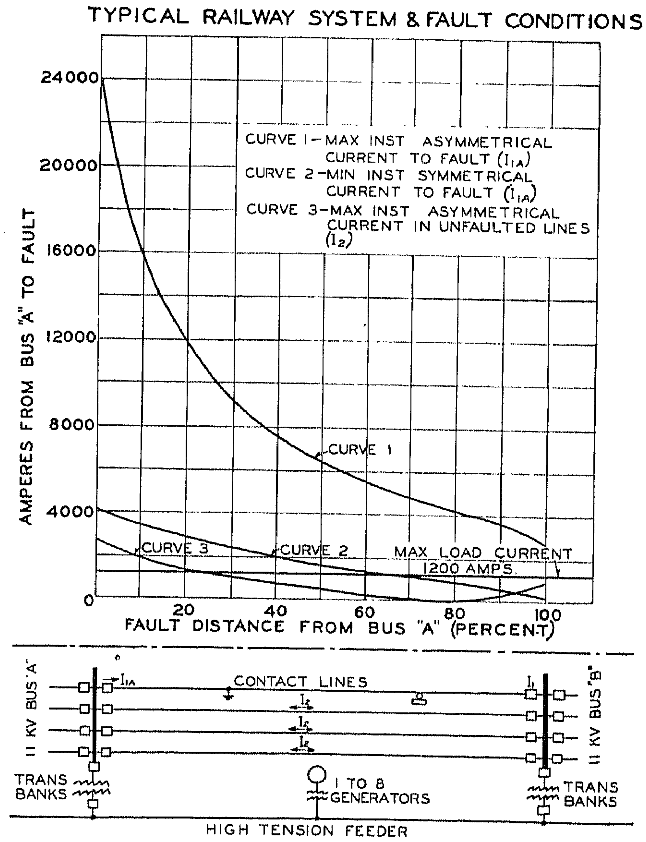

Fig. 1

of the line, the breaker nearest the fault being open, the current flow through the other end may be only 1900 amperes and the relay must operate under this condition. Simple over-current relays are obviously not applicable.

In order to secure all the advantages of the high-speed breakers, cascading or sequential operation of breakers should be avoided. This is a function of the relay system.

One suitable system of protection could be built around pilot wires. An objection to this system is found in the cost and maintenance. A second suitable system involves installing reactors in series with each breaker so that the current in the faulty line is always larger than that in the unfaulted lines. The reactors create an unbalanced current so that even with the fault just outside of the bus, relays can be made to discriminate on the unbalance. The objection to this system lies in the cost and increased voltage drop and losses due to the line reactors.

In either of the above systems provision must be made for suitable compensation for normal load currents.

A relatively inexpensive scheme of protection has been devised to give 100 per cent selectivity which permits cascading for only a very small percentage of the contact line length. It does not necessitate line reactors or pilot wires, and works from standard current and potential transformers. The relays operate in from 0.001 to less than 0.01 sec. from the time when the relay setting is exceeded.

The scheme is built about a relay which is independent of connected generating capacity. This is an over-current relay, instantaneous in its operation, which has a current setting dependent on the bus voltage. With a fault located at a definite point on a contact line, the ratio between voltage and current, which determines the operating point of this relay, is a constant. Thus the relay is equivalent to an impedance-measuring device and can therefore be set to operate for any faults within a certain

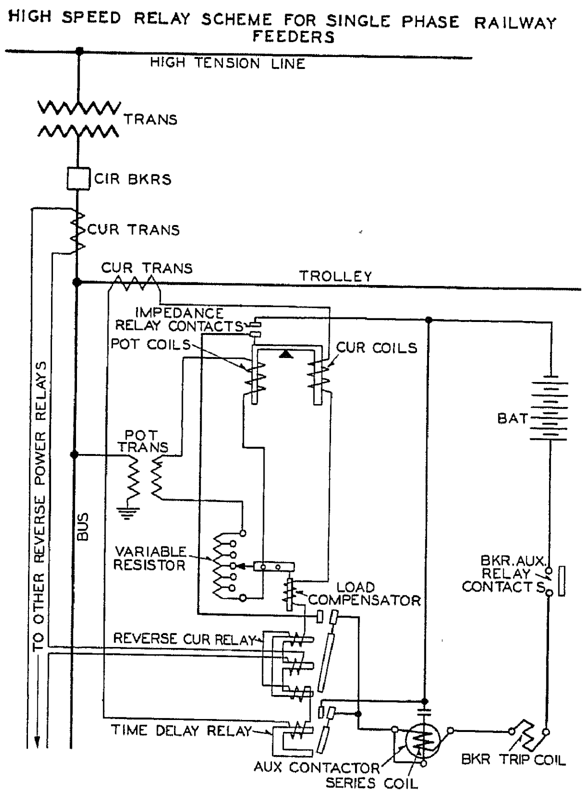

FIG. 2

distance from the breaker. The sensitivity of this relay is such that in practise, it is set to operate with faults located within 90 to 95 per cent of the contact-line length.

With faults near one end of the line, the current through the other end of the line will be small, and will correspond to approximately 600 amperes or one-half of the maximum normal load current. However, the voltage on the relay at the far end is low so that the relay will operate. Thus this device will not operate on 1200-ampere load current but will operate on a 600-ampere fault current or even less.

When a load is connected just outside of one breaker, it will effectively change the impedance of the line when faults occur at the opposite end of the line. Its effect is to reduce the impedance to the flow of current through the breaker and thus increase the likelihood of the relay operation. Therefore, in order to avoid faulty operation a presetting device has been added which changes the impedance setting of the relay depending upon the amount of load in the circuit. The diagram in Fig. 2 shows how this setting change is effected. The load presetting relay cuts out resistance, normally in series with the potential restraining circuit of the impedance relay, as the current in the line increases. Thus when loads are located on this line near the station the effect of the potential coil is comparatively large. As this load travels along the contact line toward the other station the load presetting relay slowly changes the amount of resistance in series with the potential coil so that the relay will always operate, independently of load conditions, with all faults located within 90 to 95 per cent of the distance to the next substation.

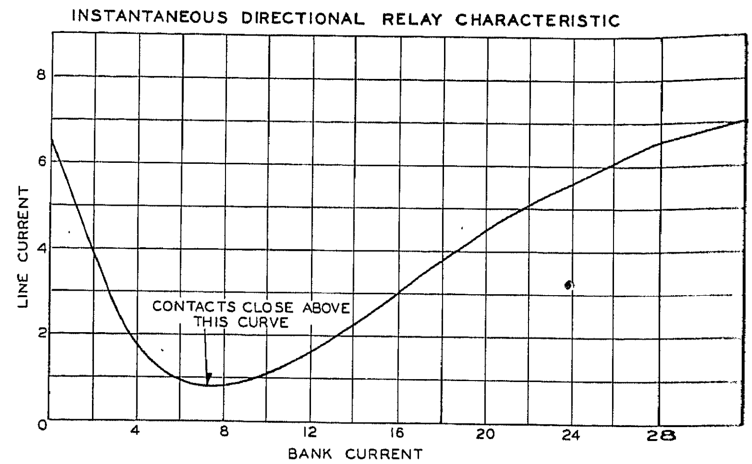

FIG. 3

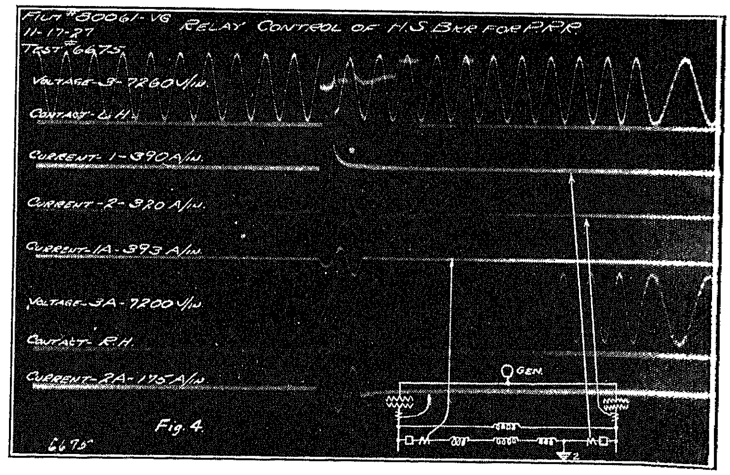

FIG. 4

As is the case with all impedance devices, a directional relay is desirable. An induction disk, or integrating device, cannot be used for this application since its time of operation is entirely too long. The principle of operation of the device used for the directional feature depends on the fact that the current through the transformer bank at a station is very nearly in phase with the current flowing in the line. As a result, the relative directions of the instantaneous current values can be used for determining the direction of operation of a polarized relay. The transformer-bank current polarizes the relay as shown in Fig. 2, and the direction of operation of the relay then depends on the line current. The relay is very fast in operation under any fault condition that can cause operation of the impedance device.

The characteristic curve of one of these relays is shown in Fig. 3. The relay has been made to operate with current in the line alone so as to be independent of whether the transformer bank is connected in the circuit or not. Adjustments on the relay permit the relay to operate at any value of line current alone, which may prove to be desirable in a particular application.

Mention has been made of the fact that this impedance relay will operate for 90 to 95 per cent of the line length, and will not operate with faults just outside of the station at the opposite end of the line. However, in that case, the impedance relay at the fault end of the line will cause quick clearing of the breaker at that end, and thus leave only the breaker farther from the fault to feed into the fault. As soon as the breaker at the fault is open,

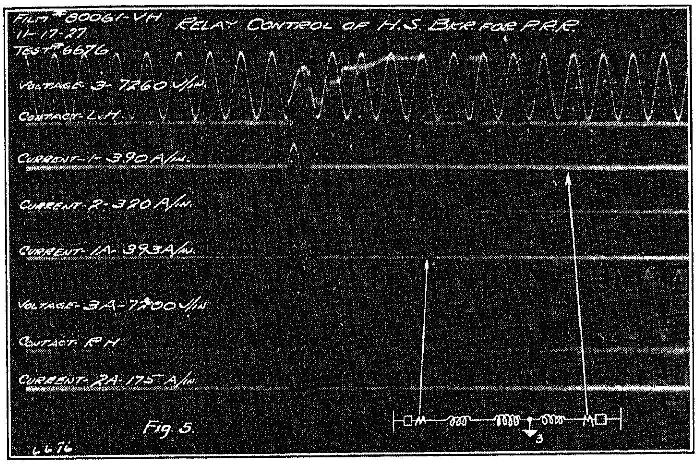

FIG. 5

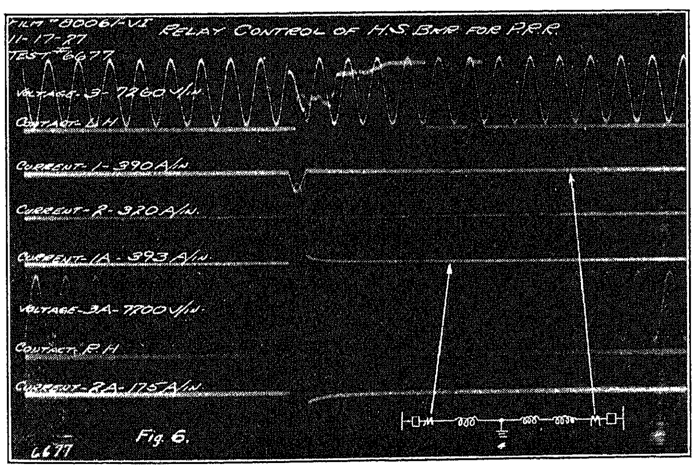

FIG. 6

the current through the breaker at the far end of the line increases to such an extent as to permit operation of a time-delay overcurrent relay. This relay operates after a time delay of approximately 1¼ cycles to cause clearing of this breaker. Thus, the sequence of operation for faults in the area where simultaneous operation is not obtainable, is that the breaker immediately adjacent to the fault opens instantly due to the impedance relay, and then the breaker at the far end of the line opens due to the operation of the time-delay relay.

In order to determine the efficacy of this system of relaying, a test setup was made. The diagram of connections is similar to that shown in Fig. 1 and the short circuit currents are as illustrated. Fig. 4 illustrates an oscillogram which was taken on this test system. The transformer currents and line currents are shown on the oscillograph record, the arrows from the diagram indicating each particular current. The voltages on the busses at each end of the circuit are also shown. Element No. 2 represents the current flowing through the trip coil of the breaker closer to the fault in this figure and Element No. 7 represents the current in the trip coil at the far end of the faulty line. As may be seen from the operation of Element No. 2, the trip coil of the breaker at the fault was energized immediately on the occurrence of the line trouble with the result that the heavy current was cleared in approximately ½ cycle. The trip coil of the breaker at the far end of the line, as shown in Element No. 7, was energized approximately 1¾ cycles after the fault occurred. This fault was taken in a position such that sequential operation of breakers was necessary. Figs. 5 and 6 represent faults at different points along the contact line. The oscillograph elements are the same as shown in Fig. 4. The total time of clearing for Figs. 5 and 6 was less than 1 cycle, and simultaneous operation of the breakers occurred. It is to be noted that the trip coils of the breakers at both ends of the line were operated almost simultaneously.

Thus, the use of a breaker with trip magnets permits the use of any type of relays desirable for any particular installation. This permits the use of pilot-wire schemes, line reactors, impedance relays, or any other relay system which seems best to fit a particular application. It permits system changes to be made which necessitate changes in the relay system at a comparatively small cost.

The scheme of high-speed relay protection described includes many of the standard protective schemes. The relays are modifications of those commonly used. The experience gained with this system would seem to indicate that any commonly used system of protection can be modified so as to be applicable for high-speed breaker operation.

F. C. Hanker: Mr. McNairy raises an interesting comparison as to the relative inductive influence produced by a-c. railway circuits and the usual power circuits. The only important difference between these two systems from an inductive-coordination aspect is the fundamental-frequency induction from the normal operating currents. The induced voltages from an a-c. railway system are due almost entirely to the earth return loop. In the case of faults to ground, the essential difference is only one of degree and not one of kind, assuming the power system to be grounded as is normally the case.

On the basis of equal fault currents on an a-c. railway system and on a 60-cycle power system, the induced voltages for the 60-cycle system would be approximately 10 times as great as for a fault on the 25-cycle system. This is due in part to the higher coupling factor at the higher frequency, and in part to the small earth current, which in the case of a four-track electrification is only approximately 25 per cent of the total return current, the rails carrying 75 per cent of the return. In the case of the electrification mentioned by Mr. Graves in his discussion of Mr. Wilcox's paper, the total fault current flowing from one station to a fault at an adjacent station is approximately 10,800 amperes. The 60-cycle current causing the same induced voltage would be $\dfrac{10{,}800}{2.4 \times 4} = 1125$ amperes, a value which is exceeded on many power systems for faults to ground. It is important to note that in the case of the railway system, the induction in sections not adjacent to the fault will be negligible. This is by no means true in the case of power transmission systems where the fault current will be of substantially the same value for parallels of several times the length of a normal railway distribution section.

Mr. McNairy makes the statement that the induced voltage from railway systems will be more frequent and of greater magnitude than the disturbances set up by an ordinary power circuit.

While it is undoubtedly true that such disturbances will occur with greater frequency on a railway system, we feel that the voltage for an equal exposure will be higher for the power system. Therefore, the only way in which we can reconcile Mr. McNairy's statements is on the basis of unequal exposures.

It seems to us that the outstanding factor in the coordination problem arising from a railway electrification is due not to the peculiar characteristics of the electrification system, but principally to the severe exposures which were created early in the development of the railway and communication services before the coordination problem was appreciated.

We note that Mr. McNairy states that a breaker and relay system designed for one-cycle operation will be the most desirable from an inductive-coordination standpoint. An effort to produce a faster breaker would probably cause undesirable transient induced voltages. This has been the basis of the design of all our high-speed a-c. circuit breakers, including the original New Haven breaker designed in 1922.

In Mr. Grave's discussion of Mr. Wilcox's paper it was brought out that on an actual system there were certain conditions of minimum generating capacity which required breaker operation on currents as low as 600 amperes or less, while under maximum conditions the breaker should not open on currents as high as 3900 amperes, this value being the sum of load current and current flowing to the fault in the good lines. That is, at the remote end of four parallel lines the faulted line may be carrying a current of 2700 amperes, the trolley with load may have a current of 3900 amperes, and the other two unfaulted trolleys may be carrying a current of 2700 amperes. Under minimum generating conditions, the faulted trolley current will be 600 amperes or less, the loaded trolley 1800 amperes, and the other two unfaulted trolleys 600 amperes. Under such conditions, will the protective system described by Mr. McNairy prevent the loaded and unfaulted lines clearing before the unloaded faulted lines? This situation would appear to be even worse if there are only two contact lines in service. It would appear that if the tripping point is set high enough to avoid clearing the loaded unfaulted lines, even sequential action could not be depended upon to clear the faulty line in such a case as Mr. Graves points out, since even after the breaker at the faulted end of the line has opened, the current at the other end may not exceed 1900 amperes. It may be possible to proportion the loading and saturating resistors to cover such a range. I should like to hear some quantitative data from Mr. McNairy on this point.

The trip-coil currents plotted by Mr. McNairy in Fig. 4 are based on a symmetrical short circuit. The duration of the first loop of current is frequently more than ½ cycle, and from his equations it would appear that if we assume $y = 45$ deg., the trip-coil current would pass through one of the flat spaces shown in the figure before having its first initial rise. This would mean that there would be no distortion in the holding magnet until the second current loop, which would mean more than ½ cycle delay before the breaker starts to open. Further, there is some doubt about Eq. 9 and a later one which make it difficult to predict what the effect of an unsymmetrical short circuit would be, and it would therefore be desirable to ask Mr. McNairy to explain further this phenomenon regarding an unsymmetrical fault.

Sidney Withington: It is of considerable interest that the apparatus described by Mr. Bardo, which represents the first examples of its type to be placed in commercial operation, should have proved so successful. The circuit breakers were built, as Mr. Bardo says, after some hesitation on the part of the manufacturers, who perhaps naturally were not enthusiastic in making development of this nature which the quantity then immediately in sight did not apparently justify placing upon a manufacturing basis. Subsequent demands are, however, an indication of the value of this type of equipment and the expense of this initial development has undoubtedly been warranted.

The operation of these circuit breakers has on the whole been very satisfactory, especially considering the fact that they represented a type of apparatus of rather radically novel design as compared with circuit breakers previously available. The difficulties which have been experienced were mostly of a minor nature and in practically all cases did not prevent proper clearing of the circuit. In most of the instances a minor revision in design has prevented a repetition so that in the future even better records may be confidently expected.

The installation has been of value in that by quickly clearing grounded circuits inductive effects on closely paralleling communication circuits have been prevented without consideration of booster transformers or other undesirable apparatus, and damage to the power distribution system on account of arcs at the point of fault has probably, in some instances at least, been eliminated.

It is entirely probable that on account of the obvious advantages in quickly clearing a circuit disturbance the use of high-speed circuit breakers may be expected to increase rapidly with the extension of heavy traction electrification.

P. H. Hatch: The problem of adequate circuit-breaker protection for electric locomotives and cars operating on the a-c. single-phase system is becoming more and more important as the magnitude of power supply is increasing. As Mr. Brown pointed out, sufficient space is usually unavailable on rolling stock to accommodate a circuit breaker capable of rupturing a dead short circuit. This has meant, on most electric railroads using a-c., that what circuit breakers have been supplied are used essentially as oil switches. Some method, therefore, must necessarily be developed for protecting locomotives or cars against the disastrous effects of short circuits occurring in the high-tension apparatus or wiring. On the New Haven, this has taken the form of a time-element relay so adjusted that the circuit breakers on the locomotives or cars, in case of short circuit, will not operate until sufficient time has elapsed for the sectionalizing breakers in the feeder and trolley circuits to trip.

It would seem that some arrangement for isolating a short circuit on a unit of rolling stock might be developed which would combine the advantages of lowering the pantograph automatically and at the same time introducing a definite time element between this operation and the appearance of the short circuit, which would give the sectionalizing breakers time to act. Hence, if for any reason the sectionalizing breakers have failed to act and the short circuit hangs on, the locomotive or car will be isolated. This, of course, involves the possibility of the power arc burning the overhead line in two, but where safety of personnel might be affected, this feature could easily be risked.

Referring again to Mr. Brown's paper, the development and application of high-speed circuit breakers for controlling the power supply introduces the problem of obtaining a relay sufficiently sensitive to operate when the current to the section affected is broken in less than a cycle's time. This has been very adequately dealt with in the paper referred to.

It takes little imagination to understand the many advantages of interrupting a short circuit before it has reached dangerous proportions. The general application of high-speed current-rupturing apparatus should go far toward simplifying the problem of protecting locomotives or cars. This will result in increased safety to operating personnel as well as substantial decrease of material damage.

J. W. McNairy: Mr. Wilcox's paper makes a statement that, with high-speed d-c. breakers, limitation of the magnitude of the short-circuit current is the only important factor in preventing flashover. I inferred from his statement that, in his opinion, the width or duration of the peak of the current curve, as shown by oscillogram, is of no importance. In this connection, I am particularly concerned with the synchronous converters when fed through a-c. lines of considerable reactance, where the short-circuit current is supplied largely from the kinetic energy of the machines. Limitation in the amount of kinetic energy

taken out, (and the rate is high at excessive currents), is of considerable importance in preventing flashover because of the unbalance in armature reactions.

I should like to ask also if it is not practically impossible to stop the current rise on short circuit below the commutating value of a machine, making it, therefore, necessary to limit the time the current is above the commutating value to less than the length of time required for an arc to be carried by a commutator segment from one brush to another.

In the paper by Messrs. Monroe and Allen I wish to comment on the statement that the calibrating means, using reluctance in the magnetic circuit, is not as accurate as it should be. I should like to ask Mr. Monroe whether he feels that the inaccuracies are due to the use of the principle of magnetic reluctance, or are due to the method of utilizing the principle in present designs. I also inquire as to whether he has encountered sufficient inaccuracies from such a source to upset selective operation on this system.

Another comment I should like to make is on the statement that it is not possible to hold the high-speed breakers closed where it is desirable to burn off short circuits. A simple method can be provided with breakers of this type whereby an operator by means of an emergency button can increase the holding-coil strength to any desired value, and thereby obtain any tripping value desired for emergency conditions. Such a system may, of course, be operated by supervisory control.

One further statement I am interested in is that with reference to the high-voltage surges induced by high-speed operation, that is, that a voltage approaching twice normal may result across the circuit breakers in the d-c. circuits when operating. I believe this is a normal phenomenon with any type of circuit breaker.

When the short circuit occurs at the end of a feeder and is opened at the substation end, the inductive voltage of the feeder is opposite in polarity to the normal system voltage. While an oscillogram of the voltage across the contacts of the breaker will show double voltage, the voltage of the feeder in front of the substation changes from plus to minus, the actual voltage not being appreciably above the rating of the system.

A more important case is the operation of the circuit breaker on a locomotive where the voltages are additative. These need not be high-speed—any of the usual types of breakers may give voltages in the same order of magnitude as the high-speed breaker. This is particularly true since the high-speed breaker is effective in limiting the short-circuit current to a value much smaller than the short-circuit value, and it is, therefore, possible to break the circuit in less time because of this lower initial current.

Caesar Antoniono: In Mr. Wilcox's paper the statement is made, "Where feasible, a solid butt contact without auxiliary arcing tips becomes very desirable, etc."

That is a point about which I disagree with Mr. Wilcox. I don't think that a solid butt parallel contact as described in this paper is practical. When the breaker opens there will be arcing and burning at the top of the contacts. Any blisters that are caused by the arc will affect the alinement of the contact.

If there is any disturbance of alinement you have to cut the face down and in the field this takes a long time. For that reason I claim that the breaker is not practical from an operating point of view.

In Mr. Monroe's paper, which covers a different design of breaker, there is the statement, "Care of the high-speed circuit breaker contacts has been found to be almost unnecessary." That is a practical breaker from an operating point of view. In the same paragraph it says, "Due to the secure manner in which they are held together magnetically, instead of relying on a spring and latch arrangement." We find at times it is desirable to have the latch breaker rather than the magnetically held, for the reason that on interurban service, where interruptions of power are likely to occur very often, magnetically held breakers will open and then there is trouble in reclosing under low-voltage condition before the voltage is reestablished. Therefore, from experience I believe that there are conditions under which the mechanically latched breaker is preferable.

D. C. West: The term "high-speed" is relative, and assumes a finite meaning only when referred back to some standard of comparison. Since the real necessity for a d-c. high-speed breaker lies in the protection of 60-cycle synchronous converters, the speed required to protect such a machine, on dead short circuit across its d-c. terminals, is quite generally accepted as the criterion in d-c. practise. This has established the nature of present commercial designs, and the resulting breakers are capable of considerably higher speed than that which will provide quite adequate protection for other classes of conversion equipment, for motive equipment, or for d-c. distribution systems.

In order to understand the necessity for the very high speed required to protect a 60-cycle synchronous converter, consideration must be given to the inherent characteristics of the machine itself. It must also be borne in mind that although the 25-cycle converter possesses the same fundamental characteristics, the 60-cycle machine is considerably more susceptible to flashover because of its much more restricted design possibilities. The idea seems to be quite prevalent that a high-speed breaker protects a synchronous converter solely by virtue of the facts that it limits the ampere-seconds in the d-c. short circuit, considered from standpoint of heating under the brushes, and that it limits the peak value of current to be commutated. While these are undoubtedly important factors, the major effect is in the limitation of the angular displacement of the rotor from its no load phase position. Under normal conditions, the a-c. and d-c. components of current in the armature windings are opposed, and of such relative magnitudes that the resultant average armature reaction is approximately 15 per cent of that in a corresponding d-c. machine. The design constants of the machine affecting commutation are necessarily proportioned accordingly. On the sudden rise of d-c. incident to a short circuit, however, the machine acts temporarily as a d-c. generator, taking its energy from the inertia of the rotor. The a-c. builds up and supplies energy to the short circuit only as the rotor delivers its energy and drops back in phase position. This results in a temporary unbalance of the a-c. and d-c. components, with the latter greatly predominating and setting up a high armature reaction. Then when the d-c. is suddenly interrupted there is a large unbalance in the opposite direction, due to the fact that the a-c. continues to flow in proportion to the angular displacement of the rotor at the time the d-c. circuit is opened. The energy component of this follow-up a-c., which tends to restore the rotor to its no-load phase position, results in an excessive armature reaction since there is no opposing d-c. component in the armature windings. It is this armature reaction which, in most cases, is principally responsible for flashover of synchronous converters. In other words, such a machine will successfully commutate, for short periods, very large values of direct currents which, if too suddenly interrupted, will cause the machine to flash over.

The high-speed breaker must, then, limit the amount of energy taken from the rotor, and hence the angular displacement at the time of interruption, to such a value that the interruption of the d-c. circuit will not result in flashover. In speaking of d-c. high-speed breaker performance, the time to the point of current limitation, which with a given machine and circuit determines the peak value of current, is a better indication of its protective ability than is the time for total interruption. In fact, it would be preferable, having limited the current within a certain time, to reduce the current quickly to a value corresponding to the rotor phase displacement, and then reduce it very slowly to allow the rotor to recover at approximately the same rate and therefore maintain more nearly balanced relations in

the armature. This is an impossible characteristic since the high magnetic blow-out effect which, as the author has explained, is necessary for high-speed limitation, also produces a high current decrement. It is possible to obtain the same effect, however, by applying the breaker to shunt a current-limiting resistor in series with the machine. Opening of the high-speed breaker then reduces the current to a value as determined by the resistor, usually two to three times machine rating, and the circuit is then interrupted by another breaker of ordinary speed.

Mr. Wilcox has pointed out the rather narrow design limitations which are imposed by the necessity for extremely high speed in the protection of 60-cycle synchronous converters. In order to provide protection under all operating conditions it is essential that the breaker be capable of this speed on *OCO* as well as on *CO* cycle. The design could be materially simplified by sacrificing a few thousandths of a second in speed on *OCO* operations, but the machine would not be protected in the case of the breaker being closed in against a short circuit. The breaker shown in Fig. 1 of the paper by Mr. Wilcox, was recently tested by the Commonwealth Edison Company at Chicago. The accompanying Figs. 7 and 8, show the oscillograph record of two of these tests in which a dead short circuit was applied to a 3000-kw., 600-volt, 60-cycle, 400-rev. per min. synchronous converter. Fig. 7 shows an *OCO* cycle and Fig. 8 shows a *CO* cycle. Within the accuracy of scaling values from the oscillogram, the speed and peak value of current are the same in both cases. The current was limited to 435 per cent of machine rating in 0.075 sec. and was completely interrupted in 0.014 sec.

J. B. MacNeill: Mr. McNairy discusses frankly the relative merits of oil and air circuit breakers as applied to contact-line service. I should like to add a few points to that discussion.

1. Regarding the effect of repeated operations on the two types it should be pointed out that it is the depreciation imposed by the short circuit on the breaker which determines its fitness for further service rather than any inherent quality of the design. The air breaker described by Mr. McNairy will open repeated short circuits. A properly designed oil breaker such as described by Mr. Wilcox will do the same. Each device, by reducing the duration of arcing to approximately one-half cycle, at the same time reduces the depreciation of the structure, whether this be oil depreciation, contact burning, or arc-chute charring. Without doubt, proper oil breakers will give service continuity and maintenance cost comparable to air breakers.

2. The space required by the air breaker seems to be considerable. Fig. 2B would indicate a length of approximately 12 ft. and a height of approximately 10 ft. 6 in., or a volume of approximately three times that of a comparable oil breaker.

3. It is questionable if insulation integrity even for 12,000-volt designs can be secured with an air breaker comparable to an oil breaker. The design shown in Fig. 7 of Mr. Wilcox's paper will stand 150,000 volts test. The same test on an air breaker would seem very difficult to secure.

4. I should like to ask Mr. McNairy if he considers the form of the current wave shown in Fig. 7 to be quite desirable. There seems to be considerable distortion on the last part of the half cycle. This is probably due to the enormous rate at which energy is expended in the arc. The statement is made that "energy is liberated in the chute at a maximum rate of 200,000 kw." when opening a short circuit of 30,000 amperes at 14,000 volts or 420,000 arc kv-a. This seems to be a very large rate for arc energy made necessary by the inherent limitations of an air breaker.

A device which would open the circuit after having pulled a low-resistance arc would, of course, reduce arc energy and incidentally would not distort the current wave form with consequently beneficial effects upon induced voltages.

5. Mr. Antoniono raised a question regarding the use of solid moving contact terminals of the high-speed d-c. breaker. Four years ago that was quite a new construction and naturally many of our older people questioned it the same as Mr. Antoniono has. It had to run the gauntlet of a great many tests, and after proving itself rather more satisfactory than average, it was accepted. It was new and would not have been accepted unless it was quite satisfactory. It has advantages in that it allows an exceedingly small moving contact to get high-speed operation.

L. R. Ludwig: Mr. Brown's paper brings to light an interesting trend in railway electrical engineering. Prior art has given us railway systems which, in addition to the major portions such as motors, require a good deal of auxiliary apparatus for protective and other purposes. Furthermore, protective apparatus has been required at many points within the system and on rolling stock itself. The concentration of this protective apparatus and the consequent elimination of part of it, in so far as this elimination is compatible with operating security, is a big step toward making electric operation economically comparable to that of steam, and so gaining the flexibility which electrical operation provides. It seems, therefore, that too much admiration cannot be shown for the combination of equipment which makes possible removing breakers, their mass and menace, from locomotives and cars.

One feature of the operation with pantograph-lowering relays which may be worthy of discussion, is the high-impedance transformer fault. That is, a fault to ground of a few turns of the transformer may not cause sufficient current to flow in the contact line to operate the substation breakers. The fault would probably grow more serious, and ultimately burn itself to ground at such a point in the transformer that the substation breakers would operate. This would entail additional destruction, however, and it seems that some measure of protection has been lost. It is almost obvious that the additional risk is cheaper than the eliminated breakers; nevertheless, it would be desirable to inquire if the last increment of protection cannot be gained without using the breakers. It is particularly necessary to protect the locomotives as completely as possible.

Two means of gaining this protection to high-impedance faults on the locomotives are self-evident. The first is the use of a small breaker on the locomotive, with proper relaying so that this breaker would operate only in case of a high-impedance fault. The second is a means of deliberately short circuiting the contact line if a high-impedance fault occurs in the transformer, and so forcing early operation of the substation breakers. Differential relay protection would give a full measure of protection to the transformer primaries, but only a partial protection of the secondaries could be secured. Further, the first method would require a breaker, and the second would possibly meet with some objection to short circuiting the contact line.

A striking means of gaining full protection presents itself as an academic possibility at least, if a protective system such as described in the paper "Superimposed High-Frequency Currents for Circuit Breaker Control" were used. It would mean actuating the substation breakers by connecting the contact line to ground through a condenser in case of a high-impedance fault, thus short circuiting the high-frequency system, but not the main power system. Also, full protection of both primary and secondary could be gained by using the differential of primary and secondary high-frequency voltage for relay operation.

Chester Lichtenberg: These papers give the impression that high-speed circuit breakers are new. They are not. They have been in service on electrified steam railroads for over 15 years.

There are two classes of high-speed circuit breaker. One has a mechanical latch for holding the contacts closed. The other has a magnetic device for holding the contacts closed. They should not be confused. A high-speed breaker will operate equally well when either means of holding its contacts closed is used. The type of contact-holding mechanism must be chosen for the particular application.

In some cases the high-speed circuit breaker has been con-

demned because when opened it may cause flashover of a d-c. machine. In such cases it is probable that the position of the breaker has been incorrectly chosen. It has probably been placed on the positive side of the machine. It has not been shunted with resistance. As a result, the current has been abruptly reduced from a high value to zero. So flashover has occurred.

Placing a shunt resistance across the high-speed breaker will not prevent the flashover of a machine if the combination is in the positive lead. If, however, the combination is inserted between the negative brush ring and the commutating or compound-pole windings, short circuit from flashover is prevented. The high-speed breaker on opening abruptly prevents the current's rising further. The arc drawn in the chute inserts resistance in the circuit. The current is quickly reduced to a relatively low value as set by the fixed resistor shunted across its contacts. Then another circuit breaker opens clearing the circuit. The resistance prevents an abrupt circuit clearing. It limits the resultant voltage rise to a relatively small value, too small to start arc-over. Being in the negative side the opening of the high-speed breaker would open any circuit through a flashover. For the flashover, if it occurs, takes place between positive brushes and ground *through the negative brushes*!

J. T. Hamilton: (communicated after adjournment) We operate multiple-unit cars having pantograph-lowering relays of the Westinghouse Electric & Manufacturing Company, 371-S2 and U.C.-8 types.

We have found that these relays protect the high-tension transformer windings but do not offer much protection for the low-tension windings of the main transformer, if this short circuits. In some cases where this short circuit has not been sufficient to operate the anchor-bridge circuit breakers, it results in the transformer being totally destroyed due to the overload being sustained.

Where one-car trains are operated, it may be necessary for the motorman or engineer to have access to the pantograph-lowering relay so that it can be reset. This is the practise followed on this property, our motormen being instructed that the relay in question can be reset if no damage is visible on the transformer of the car. We have found that the pantograph-lowering relay has operated sometimes without proper cause. As noted in Mr. Brown's paper, this may be due to the design of the relay in question.

On a-c.—d-c. equipment operating on a zone with d-c. overhead construction, it may be desirable to have a means of disconnecting the pantograph circuit from the main transformer, thereby preventing the d-c. from passing through the a-c. pantograph (if it should be raised accidentally) and then through the transformer with the resultant damage. This is easily taken care of by suitable a-c. circuit breakers.

C. L. Doub: (communicated after adjournment) From the standpoint of connection with the Illinois Central Railroad electrification in the layout of this distribution system and in the design, construction, and initial operation of the tie stations, I wish to amplify several points of the paper by Messrs. Monroe and Allen.

The large number of breaker openings during the early operating period has at times been referred to as "hair-trigger" action and cited as a fault of the high-speed breaker. It is significant that after this initial period the number of breaker openings reduced to a normal value (and in fact on some days there have been no breaker openings whatever), though changes have not been in the tripping circuits of the breakers. In the system there are 34 feeder sections which are fed by a total of 70 high-speed substation and tie-station breakers. It is therefore very well established that the so-called excessive number of openings was due to conditions other than the circuit breakers. Although making it difficult to locate the cause of the openings the breakers undoubtedly prevented a great deal of minor burning of car equipment and flashing of converters, and in all probability saved some cases of major damage. These excessive openings did not cause train delays, since breakers were immediately reclosed by substation operators or by supervisory control. On the other hand, they may have saved train delays, through preventing damage of equipment.

The several serious train delays charged to the breakers were due to defects in reset mechanism rather than in tripping, on account of which it was difficult to pick up a large legitimate load of rather steep wave front. The change in reset mechanism has entirely eliminated this fault.

Failure of selectivity occurred practically in no case excepting where two short parallel sections fed stub from a substation and were tied together by tie-station breakers. In this case selectivity is required between a tie-station and a substation breaker carrying the same current, with the same wave front, the only difference in the breakers being in excitation of holding coils from the line and from a battery, respectively. Even under such a severe requirement, selectivity is actually obtained except when the short circuit is remote from the tie station. In such a case the tie-station breaker holding coil receives too small a drop in voltage to make enough difference in speed of operation, since both breakers inherently have high speed. Other cases that have been considered possible failures of selectivity were in all probability due to bridging of section breaks by pantographs at the time of the transient, thereby actually imposing the fault on two or more feeder sections. The probability of this bridging is not at all remote in view of the large number of overlapping sections at interlocking plants and the considerable number of pantographs that are moving at one time.

Another outstanding feature is the great reliance on the high-speed breakers, which is unparalleled in any other similar heavy-duty apparatus. In spite of the large number of breaker openings no case was found where maintenance required more than light dressing of the contacts at periods of six months or more. At several times extensive tests were made involving 25 or more direct short circuits adjacent to circuit breakers within a short time and it was not even considered necessary to inspect contacts after such tests.

The simplicity of auxiliaries and circuits can well be emphasized. No relays or circuits external to the breaker are required for tripping. On this system the only relays are for reclosing and for supervisory control. Although the breaker itself is more intricate than the ordinary breaker, it is sufficiently strong and reliable to cause no difficulty in maintenance.

Practically all of the disadvantages of the breaker on this system have been eliminated or overcome. One disadvantage which cannot readily be eliminated is the difficulty of calibrating the breaker in the field, since currents of actual tripping value are necessary. Thus far there have been no differences in calibration demanding such field work, and perhaps the method supplied for correction for contact wear will prove sufficiently accurate for practical purposes.

On the whole, the disadvantages of the high-speed breaker in this installation have been so far overshadowed by the advantages that they need be given little weight.

D. C. West: (communicated after adjournment) In any sectionalized d-c. railway network such as that described by Messrs. Monroe and Allen, the feeder equipment must include two rather distinct operating features if a high standard of service is to be maintained. First, it must be selective between parallel feeder sections, so that only one section is isolated in case of fault. Second, it must provide positive discrimination between legitimate loads and faults. Since the latter of these two requirements has proved to be the more difficult, a brief statement of the problem, and of what has been accomplished in its solution, should be of interest.

The business of an electrified railway is to operate trains, and the electrical equipment is but a means to this end. It is essen-

tial that the feeder equipment protect the *service* as well as the distribution system, and it is with this in mind that the manufacturers have attacked the problem. Railway men are quite in agreement that the ideal feeder breaker would be one which would remain closed on any legitimate load to which it might be subjected under either normal or abnormal traffic conditions, and yet would trip out on any fault which might occur on the feeder section to which it is connected. The range of discrimination necessary to accomplish this will vary with the class of service and the type of distribution system, and for different traffic densities within a given system. In a very few cases the minimum short-circuit current will be of magnitude sufficiently greater than the maximum legitimate load peak to permit the use of an ordinary overload device. Usually, however, it

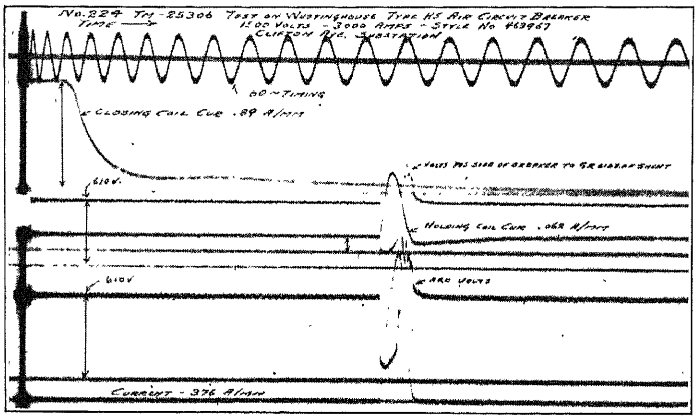

Fig. 7

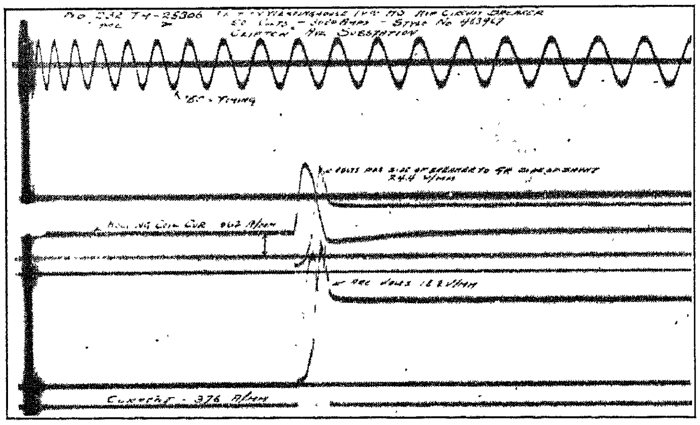

Fig. 8

will be found that the possible legitimate load considerably exceeds in magnitude the value of short-circuit current incident to a fault at the most remote point on the feeder section. In such cases discrimination is possible only through the use of some form of impulse tripping.

It is fundamental that a legitimate overload on a railway feeder is the result of a traffic congestion. Railway men will readily appreciate the fact that it is at such times that it is most important to stick to the load up to the very limit of the current-carrying capacity of the feeder circuit. In other words, a legitimately overloaded railway feeder becomes a preference circuit which must remain closed, as long as the circuit is not at fault, in order to clear up the congestion. To open the breaker under such conditions, due to the magnitude of legitimate load, only makes matters worse and presents the possibility of serious delays to traffic. In considering the range of discrimination necessary, then, the maximum legitimate load will be that required to handle such traffic congestions as may occur on the particular feeder in question.

As has been brought out by the authors, the d-c. high-speed breaker, when equipped with an inductive shunt, has a combined overload and impulse tripping characteristic, and is therefore inherently capable of a certain degree of discrimination. Its possible inherent range of discrimination is determined within limits, by degree to which the overload feature can be minimized and the impulse feature can be magnified. The Commonwealth Edison Company, in collaboration with the Westinghouse Electric and Manufacturing Company, recently made a very comprehensive series of tests, at Chicago, on high-speed breakers for supplying power to the feeders of the Chicago Rapid Transit Company. It was demonstrated that the inherent range of discrimination was quite sufficient for the type and proportion of feeder sections comprising probably the major portion of the Rapid Transit system. The relatively high range on these breakers is made possible by raising the steady-current tripping characteristic to such a high value that it is well above the possible peak value of legitimate load swings, even under heavy traffic concentration. The breaker is therefore responsive principally to rate of rise and is affected to a relatively small degree by the magnitude of current flowing in the circuit. For example, with the breaker adjusted to a point well under the setting necessary to trip out on the 6500-ampere current increment due to a short circuit at the most remote point on one of the longer feeder sections, the steady-current tripping value is well above 15,000 amperes. The 8-car Rapid Transit trains require an accelerating current of about 2500 to 3000 amperes, and an oscillograph test on a 6-car train of the Chicago, North Shore and Milwaukee showed a maximum of 5250 amperes during acceleration. The actual discrimination obtained depends principally on the difference between the characteristic of the maximum single increment of load current, and that of the most remote short circuit. As is usually the case, the maximum load increment proved to be that due to the first point of control on the heaviest train. The 6-car North Shore train showed a single increment of 2670 amperes at about 8.4 millihenrys inductance. The inductance in the circuit of the 6500-ampere fault previously referred to, was about 3 millihenrys. It will be possible to handle a concentration of several trains on this section, and still isolate the most remote fault.

On most railway systems, and particularly in the case of steam-road electrification, even this relatively wide range will be found insufficient to provide positive discrimination throughout the system. By the use of properly designed relays energized from impulse transformers in the feeder circuits, it has been found possible to provide a range of discrimination sufficient to cover even the most difficult conditions encountered in service on the various types of systems. The most extreme example is probably that of the Staten Island Electrification of the B. & O. Railway, at New York, which was placed in service in 1925. Here, the high inductance of the heavy third rail made the problem particularly difficult. A feeder equipment was set to trip on a fault applied at the most remote point on the longest feeder section, and the oscillograph showed a current of 1950 amperes at the time the breaker opened. Then, with the same setting, an 8-car train, representing maximum future service, was accelerated immediately in front of the station. The breaker remained closed, although the oscillograph showed a single increment, on the first point of the train control, of 2350 amperes with a rate of rise of about four times that of the short circuit. The maximum accelerating current was 4350 amperes. Since the tripping is in no way responsive to the magnitude of current flowing in the circuit it can handle any number of such trains in a traffic congestion, up to the heating limit of the circuit, as determined by a thermostat on the outgoing feeder copper.

The system is double-track and completely sectionalized, including a tie station. Selectivity between parallel feeders is, of course, necessary and is readily accomplished by means of the same relays.

This case is cited as an illustration of what it is possible to accomplish by the use of devices designed solely for the purpose of obtaining the proper tripping characteristics. It would obviously be impossible to obtain this range of discrimination by using only the *inherent* characteristic of a device such as the high-speed breaker, in which the tripping is responsive only to the magnitude and rate of change of current. However, it is entirely possible to apply such relays to *any* type of breaker, and thus obtain the characteristic required for the particular conditions to be met. For example, it is entirely possible, through the use of relays, positively to isolate faults at all points on the feeder sections in the district between Brookdale and Harvey Substations, without the addition of any tie stations, and still permit the handling of larger trains and considerably heavier traffic.

H. C. Graves: (communicated after adjournment) Mr. McNairy has divided the time of operation of the high-speed circuit breakers into three parts as follows:

1. Time required for relay operation.
2. Time required for the separation of contacts.
3. Time required for extinguishing the arc.

He also mentions that by using breakers, as he has described, the time of relay operation can be eliminated.

To compare the speed of the breaker that uses relays, with those described by Mr. McNairy, it would be necessary that the time required for relay operation should also include the time necessary for the building up of the tripping current. Thus, if Item 1 should read: "The time required for relay operation and the building up of the tripping current," Items 2 and 3 could then be comparable on the different breakers.

Fig. 4 in his paper brings out the fact that the building up of the tripping current lags behind the building up of the line current. Assuming this wave in Fig. 4A to be a 25-cycle wave, the current rises to a maximum in 0.01 seconds, but the tripping current in Fig. 4B does not rise to a maximum until 0.016 seconds.

Also the tripping-coil current does not rise rapidly as does the line current, but rises gradually at first, and more rapidly later. This time lag is equivalent to something over ⅛ cycle, and relays suitable for this application are much faster than this. Oscillographs show that the trip-coil current builds up to a tripping value with practically no time delay after relay contacts close. Thus the building up of the trip current in the breaker as described by Mr. McNairy, is no faster, if as fast, as that described by Mr. Wilcox.

One important condition which must be met by the protective equipment on a system of this type can be described as follows: With a load adjacent to a station bus on a contact line, a secondary current of 5 amperes may flow away from the bus to the load. In Fig. 13, this current appears in the trip coil and the return path is not only through the saturating resistor but also through three other trip-coil circuits in parallel with the saturating resistor. The trip setting must be adjusted so as not to trip under these and other conditions such as the magnetizing of train transformer banks after the contact line has been disconnected, bus short circuits, etc.

After a train load has been connected until the fluctuations in the trip circuit have died out, a current increase of more than five amperes or more than ten amperes total fault current must flow to cause tripping. It is quite conceivable that this condition cannot always be met in practise.

Our objection to the scheme of connections as shown in Fig. 13 is that a change in the number of feeders connected changes the calibration of the other tripping circuits. The greater the percentage of change, the greater the effect.

If the breakers are so set that the above conditions will not cause faulty tripping of the breaker, then a comparatively large unbalance in line current must occur before the breaker will trip. If the breaker can be set so as to operate correctly under all conditions, it cannot be set so as to avoid a considerable amount of sequential operation. That is, the breaker at one end will open first and then the breaker at the opposite end will open. This is a bad condition from a standpoint of interference in signal and communication circuit, since the fault current is high and the distance of the exposure is possibly the entire distance between stations.

In Fig. 13 is shown the relay protection, including back-up relays, for a typical application. The back-up relay is shown as an impedance relay. This should prove to be a satisfactory form of protection in that it, alone, if of the induction type, should afford proper selectivity even if no other form of protection were included. However, here again simultaneous tripping of breakers at both ends of a faulty section would not take place and some time delay would be necessary.

H. M. Trueblood: (communicated after adjournment) I should like to add briefly to the discussion touching the relative inductive effects of single-phase railways and power circuits.

Aside from the other factors mentioned by Mr. McNairy, and by Mr. Hanker in his discussion of Mr. McNairy's paper, a comparison between the two systems should not, I think, overlook the greater probability, for short circuits on railway circuits, that faults will be of low or negligible resistance. Also, with multi-track roads, the inductive effects of current in the trolley-track loop may be of considerable importance in cases of closely exposed circuits, such as railway communication circuits carried on poles located on the right-of-way. Again, if a 60-cycle power line is provided with a ground wire or wires, such conductors carry a part of the return fault current, acting in this respect like the rails in the railroad case. Although they are not so effective in this function as the rails, they may carry substantial amounts of return current, especially if they are of high conductance. Mr. Hanker refers to the relatively small amount of induction in railway sections not adjacent to the fault. The significance of this, in a comparison of the two systems, depends upon the character of the exposure. While this factor is undoubtedly important so far as long, close parallels are concerned, it would be of minor weight from the standpoint of a type of exposure frequently met with, unless, in the railway case and not in the other, there is adaptation of substation location to the exposure conditions.

In Mr. Hanker's discussion, the statement that for equal fault currents the induced voltages for the 60-cycle system would be about ten times as great as for the 25-cycle railway system, is apparently based on 75 per cent rail current in the latter case. While this is a figure customarily used for four-track roads, it does not hold for a smaller number of tracks. With a single-track road, for example, the factor of ten mentioned by Mr. Hanker would be reduced to five or less. Either of these factors would, of course, be much larger than the ratio of actual induced voltages. In fact, as is suggested by Mr. Hanker's numerical example, fault currents on 25-cycle railways are ordinarily several times greater than on 60-cycle power systems, in cases where line impedance is an important factor, as it usually is where parallels are long enough to produce the higher values of induction.

A general comparison of the kind under discussion is difficult. To get numerical results, certain factors, such as line voltage, connected capacities, fault resistance, etc., must be fixed. For equal line-to-ground voltages, I believe it to be true that a three-phase 60-cycle system with dead-grounded neutral, when short-circuited to ground through zero impedance, would usually induce larger voltages than a single-phase 25-cycle railroad similarly short-circuited, provided exposure conditions are the same and such as to make the inductive effect of the current in the trolley-track loop negligible. This preponderance of the

induction from the 60-cycle system tends to decrease with increasing length of exposure.

J. W. McNairy: The discussion by Mr. Graves, supplementing the paper by Mr. Wilcox, brings up many interesting points in connection with the selective operation of high-speed a-c. breakers applied to a network, particularly in connection with high-speed impedance relays.

The impedance of a given circuit may be easily determined from effective values of current and voltage under sustained conditions and used to actuate standard impedance relays. However, high-speed operation approaching that of other methods necessitates the determination of impedance by the current and voltage conditions existing for a small fraction of a cycle immediately following a short circuit under all possible transient conditions and presents a more difficult problem.

With low-power-factor circuits the ratio of instantaneous current to voltage varies for every point of the current wave. A relay utilizing the difference in torque between a potential restraining element and a current operating element receives a maximum operating torque on a low-power-factor short circuit near the zero point of the voltage wave where the current is a maximum. The restraining torque near zero of the voltage is necessarily relatively slight. At zero power factor there is, of course, no restraining voltage at the instant of maximum current.

It is entirely feasible to design over-current relays capable of closing contacts or mechanisms capable of unlatching in approximately 0.001 sec. after the trip point is reached. The design of an impedance device for such a speed of operation, however, is impractical because of the response to instantaneous current values and operation at the peak of the current wave where the voltage element has little or no effect.

It therefore appears essential that the speed of operation of an impedance device be limited so that the operating forces are dependent upon the effective values of both the current and voltage for at least a considerable portion of a cycle.

Further, where such a device is used, it should be noted that for a given applied voltage and a given external circuit both the instantaneous and effective values of the initial short-circuit current may vary over a considerable range. This variation results from the displacement of the short-circuit current wave and is dependent upon the instantaneous voltage at the time a short circuit occurs only and not on circuit conditions. With a completely displaced current wave the peak occurs one-half cycle after the incident of short circuit, at which time the voltage is approximately zero. The maximum current is twice that of a symmetrical current circuit, conditions being the same. High-speed impedance relays must, therefore, be set sufficiently high so that displaced exchange currents over unfaulted feeders will not operate these relays. The length of feeder which can be protected under short-circuit condition on a system of the type specified, with a symmetrical short-circuit current, is consequently limited. As a result, symmetrical short circuits at a considerable distance from a substation are likely to result in sequential operation of the two breakers at the ends of the faulty feeder.

It would appear, in view of the above, that a selective system based on the accurate determination of impedance from current and voltage conditions existing for a fraction of a cycle presents many new problems not associated with the usual type of impedance relay operating at slow speed.

In this connection, an accurate impedance device capable of operating in a half cycle must be equipped with a potential element which can respond to an instantaneous reduction in voltage, such as occurs at the instant of short circuit. The application of a short circuit in front of a station, at the instant the voltage is near the peak of the wave, requires that the current through the voltage restraining element of the relays at adjacent stations be reduced to a fraction of that existing prior to the short circuit in a very short period of time if true impedance is the basis of operation.

A further point is of interest in connection with the application of impedance relays to a system of the type which has been repeatedly discussed. The heavy current resulting from a short circuit at or near one substation greatly reduces the voltage of the high-tension line feeding adjacent substations. Impedance relays so designed that they will not operate with an exchange current of 2700 amperes over unfaulted feeders, with greatly reduced voltage, inherently require a relatively large current under load conditions where the restraining voltage is not appreciably reduced. This point is of very considerable importance in connection with any system where all substations are fed from the same source of power.

Sequential operation of circuit breaker at the two ends of faulty feeder, with short circuit near one station, is, of course, detrimental only when it results in a longer duration of the current over the feeder. When operating devices, such as impedance relays, receive an impulse only just sufficient to operate the resultant unbalanced torque between operating and restraining element which is relatively slight, full speed operation of the relay is difficult to obtain. Under such conditions the total duration of the short-circuit current over the feeder may not necessarily be shorter than that obtained by devices which do not initiate the operation until the second half cycle of the short-circuit current. This is particularly true where a considerable portion of a half cycle is required before release of the relay mechanism.

Referring to Mr. Hanker's discussion, there seems to be some misunderstanding as to the characteristics of a saturated current type of tripping circuit applied to the breakers described in the paper. The impulse voltage generated by the saturated current transformers is not a function of the total current through the corresponding breaker, but is a function of the current applied suddenly under short-circuit conditions.

If, therefore, the breaker supplying a faulty feeder is carrying a load of 1200 amperes and a short circuit occurs, resulting in an additional 2700 amperes in this feeder as well as three paralleling feeders, the initial current of 1200 amperes has practically no effect on the tripping circuit of a breaker connected to a faulty feeder. The voltage generated by this tripping circuit is proportional to the 2700 amperes increase resulting from the short circuit and is equal in the tripping circuits of all feeder breakers carrying the same increase. The only return path for the tripping current is through the saturating resistor common to all breakers, the resistance being sufficiently high to limit the current below the tripping point of the breakers.

By changing the value of the saturating resistor the ratio of the tripping point with a simultaneous current increase to the tripping point with a current increase through one feeder only can be made as great as desired. The trip point for a simultaneous current increase through all breakers can be made infinitely large by open-circuiting the saturating resistor.

It should be pointed out that the setting of the current-transformer trip is not determined by steady load requirements of the feeder. The limiting condition is the maximum increase in load which can take place instantaneously on the feeder. It is entirely feasible to have a breaker of this type set to trip with a current increase of 600 amperes, at the same time carrying a steady overload of any desired value without tripping. Due particularly to starting currents resulting when transformers of locomotives or cars are suddenly energized, it seems desirable that any protective system be capable of picking up such transformers regardless of the steady load conditions. The saturated transformer trip has the proper inherent characteristic. The effect of the pre-setting arrangement described by Mr. Graves results in a similar characteristic.

The selective operation of the differential circuit described in the paper is not dependent upon accurate setting of the breakers.

Fig. 4 of the paper was plotted to show conditions with a symmetrical short circuit because this is a limiting case in which the minimum-tripping current results. The flat section of the tripping-current curve shown occurs only after the first tripping impulse has been supplied by the tripping transformers. In no case does a flat section precede the first tripping impulse. The calculations can be easily made to show the performance of the transformers with completely displaced wave by introducing a transient term in the equation for the line current. Numerous test records indicate that the tripping arrangement is, if anything, more effective when the current wave is displaced.

It should be pointed out that the exchange current betweent stations over the 11-kv. feeders results from the impedance drop in the 132,000-volt line between two substations and the step-down transformers supplying the short circuit directly. An exchange current of 2700 amperes results only with maximum generator and high-tension line capacity. A short circuit directly in front of one station reduces the voltage of the high-tension line to a relatively low value. If the drop through the low-reactance transformer and high-tension lines is sufficient to result in 2700 amperes exchange current per feeder between stations, or a total of 9800 amperes for four feeders, on the initial short circuit directly adjacent to one station, a very considerable increase in current will be realized as soon as the heavy short circuit is removed from the high-tension line, this current being effective in tripping the remaining breaker at high speed.

Mr. Hanker evidently interpreted my statement to the effect that the desired form of high-speed breaker is one which stops the current at the first zero after the first full half cycle to mean one-cycle operation. This is not the case, however, as a short circuit involving the time of a full half cycle rarely occurs under short-circuit conditions with the breaker described. A great percentage of test records taken on breakers of the type described in the original paper shows a single loop of current, a few show two loops, the duration of which in practically all cases is considerably less than one cycle.

Regarding the question of insulation of the air type breaker, I should like to know whether or not Mr. MacNeill feels that the 12,000-volt circuit is ordinarily subjected to voltages of the order of 100,000, or whether he feels the failures are due to local operating conditions, such as dirt, smoke, etc.

There are a great many pieces of apparatus connected to a 12,000-volt railway system which are not capable of standing 100,000 volts. There is nothing inherent in the design of the air breaker to limit the insulation for any reasonable requirement on 12-kv. systems. We feel that the type of insulation which is being used for the air breaker is particularly suited for the mechanical shocks of high-speed operation.

Another question raised was whether or not high voltages were likely to result from too rapid decrease of the current such as shown by Fig. 10. The particular figure referred to by Mr. MacNeill had plotted on it the voltage taken from the oscillogram. The voltage was 10,000 volts. Voltages have been checked by other recognized methods and I can say quite frankly that direct comparisons have shown less tendency to high voltage with the air breaker than with the oil types.

There has been no record published covering the liberation of energy in the oil breaker at rupturing currents near its interrupting ratings. It is my impression that with the heavy currents of 30,000 or 40,000 amperes there are a great many effects that come into operation of the circuit breakers, other than the magnetic blow-out effects, tending to cause high voltage. We know there are certain types of oil breaker which depend largely on explosion effects for opening the circuit.

I have an impression that any type of oil breaker, by virtue of those explosion effects, is quite likely to decrease the current more rapidly than a breaker where there is not available oil to furnish gas pressure for explosion. Some of this effect is present in an air breaker but we find from the experimental work we have carried on that the difference in this effect between the lighter and heavier currents is not nearly so pronounced as in the oil breaker.

Mr. A. C. Graves, Jr. has brought up some additional points in his discussion submitted after adjournment that require further consideration.

The statement was made that the tripping current as shown by Fig. 4A of the original paper does not reach maximum until 0.016 sec. after the beginning of the short circuit. It might be inferred that under any short-circuit conditions the breaker in question would not receive tripping current until the peak of this current is reached. Such a statement applies, however, only where the breaker is operating with current just sufficient to trip. Where a short circuit of any considerable magnitude is involved the trip point of the breaker is reached considerably in advance of the peak of the trip current and the breaker receives its tripping impulse in sufficient time to limit the current to a single loop in a majority of cases. The case taken for Fig. 4 is the limiting case where the current is just sufficient for operating the breaker.

As pointed out in an earlier discussion of Mr. Grave's description of impedance relay, it is difficult to see how an impedance relay can be constructed to operate on true impedance in a fraction of a half cycle, taking into account all possible transient conditions.

After all, an impedance relay receives its operating torque from the line current, this current usually reaching a maximum between one-quarter and a half cycle after the beginning of the short circuit. With the low power factor existing in short-circuit conditions, the voltage is a minimum, and, therefore, there is a pronounced tendency for the impedance relay to operate at this point of the short-circuit current wave unless a considerable time lag is introduced. While it is entirely possible to build relays which will close the tripping coil circuit in a very short time after the trip point is reached, such relays are usually not of the impedance type.

It is again pointed out that the setting of the saturated-transformer type of tripping circuit is not limited by steady load conditions. It is only necessary to set the circuit breakers so that the maximum load increase encountered in normal service will not operate when occurring on a single feeder. The limiting condition quite likely is that resulting from starting currents when energizing transformers, and any high-speed protective system which will operate in a fraction of a cycle must have sufficient leeway to prevent operation when transformers are energized at a time when the feeder is loaded near the maximum. The load pre-setting arrangement described by Mr. Graves in his original discussion of Mr. Wilcox's paper apparently permits a sudden application of load above the steady load being carried by the feeder in much the same manner as the saturated-current-transformer type.

One further point in connection with this application is that it has been repeatedly pointed out that under certain conditions on a given system the fault current over unfaulted lines between substations may reach 2700 amperes. This means that an impedance relay used for protection must be set so that 2700 amperes over the unfaulted feeder will not result in breaker operation, taking into account the fact that a short circuit at or near one substation reduces the voltage of the common high-tension system at adjacent substations to relatively small value. It is difficult to see how a relay can be made to trip at a load of 1200 amperes when the voltage is not appreciably reduced and still remain closed with an exchange current during short circuit of 2700 amperes between substations with the restraining voltage considerably reduced.

W. P. Monroe: Mr. McNairy asked two questions regarding our statement as to the inaccuracies of the calibrating mechanism.

We referred in our paper to the means of calibration which is obtained by a set screw which turns in and out of the holding-coil core and the marking of the calibration scale on a plate parallel to this screw. The scale is small but covers a considerable range. I believe it is obvious that with such a scheme of adjustment a high degree of accuracy would be difficult. He asked if this disadvantage has affected our operation. Since we have been in operation only two years and our initial adjustments are still largely in effect we believe our experience is not sufficient to enable us to know whether this will be a serious handicap. We anticipate that the wearing of the contacts of the breaker will affect the calibration somewhat.

In regard to holding in the circuit breaker on overloads, this can be done, as Mr. McNairy says, by remote control with a push-button, changing the calibration temporarily, but we were referring only to our own installation. In our unattended tie stations such a feature would entail undesirable additional supervisory control circuits.

In regard to high-voltage surges, without going into the theory of surges resulting from high-speed breaker operation on short circuits, I would say we mentioned this objection because it had been mentioned to us and we wanted to publish the fact that we had noticed no disadvantage of such effects, whether they exist in alarming proportions or not.

Formula for Minimum Horizontal Spacing of Transmission Line Conductors as Affected by Danger of Contact in the Span

BY PERCY H. THOMAS[1]

Fellow, A. I. E. E.

THE present contribution is for the purpose of deriving a logical formula to be used as a guide in the determination of the minimum safe horizontal spacing of transmission line conductors, and is offered for discussion. By minimum safe horizontal spacing is meant the least spacing that will insure safety against short circuits between conductors due to their swinging together out in the span under the influence of wind or ice, and has no relation to the separation of conductors transversely at the towers, as required for securing the necessary clearance to the tower structure. The latter separation is usually controlling, but a number of cases occurs where the getting together in the span requires a wider spacing, such, for example, as long spans, or two circuit horizontal arrangements of conductors.

Theoretical Analysis

A study of these questions shows many erratic factors bearing on the danger of contact in the span between cables *horizontally* spaced, so that apparently experience data rather than mathematical calculation must be the final dominating consideration. However, these experience data are exceedingly scanty and difficult to interpret, so that a theoretical analysis is likely to be of real value.

Steady Uniform State

Considering a transverse wind, uniform in direction and steady in strength, we have a very simple case, for all the cables will be deflected in the same direction and by the same amounts, and will maintain exactly the same horizontal separation regardless of the direction and strength of the wind, even if the wind be straight up. Even if the wind blows at an angle with the direction of the line, the same condition exists. This is a very important conclusion.

An examination of the relations involved shows that with a strong cross-wind blowing the dropping of the ice on one cable leaving another cable in the same span coated would not have much effect on the relative side-swing of the two conductors in the case of aluminium cable steel reinforced, since the weight drops with the ice removed more or less in the same proportion as the wind surface is reduced. A special study should be made in each case for copper cable, where the balance is not so close. This action of steady state side-swing giving unequal displacements from ice unbalance is governed by entirely different conditions from the general case and is not hereinafter considered.

Non-Uniform Wind Condition

When the wind is irregular in time or direction, or uneven at different points, there will be more or less tendency for the cable to depart from the true catenary curve and the possibility of contact occurs. Obviously, it is the transverse horizontal components of the deflection that tend to cause contact, not the vertical. With a strong wind blowing across the line, say 60 mi. an hour, air moves at a velocity of 88 ft. a second so that a time of perhaps 2/10 sec. elapses between the time when the air impulse acts on one cable and when it reaches the next cable in the same horizontal plane, so that there is no time for actual motion of one cable ahead of the other cable, due to the same high velocity wind impulse. Furthermore, it is exceedingly unlikely that with a *high velocity* transverse wind, there can be any great change of velocity or direction of the air in traversing the short distance between adjacent cables. In fact, the direction of the air must in general be substantially parallel to the ground, as there is no place for air to go elsewhere. This means that all cables in the first approximation are subject to the same transverse air impulses at any one instant of time, substantially. This is the reason, no doubt, that trouble with wires getting together in the span is so rare. Where the surface of the ground is curved or local obstructions exist close to the line, eddies will of course be produced. This is a vitally important case and will be considered later. The only exception would appear to be a cyclone on a small scale, with an axis inclined to the vertical by a large angle, this being practically beyond any experience of which the author is aware. But there are actual conditions in which cables have got together so that the necessary irregularities must sometime occur.

The most important active factor in preventing contact in the span with transverse winds is, no doubt, the restraining force of the tension in the cable which tends to prevent deformations of the catenary by the wind. In long-span construction, this tension is of very material amount and has a remarkable restraining effect. To deflect a vertically hanging wire carrying a 5000-lb. weight, one degree from the vertical will require a horizontal force of 85 lb. applied at the weight. A wind producing a pressure of 8 lb. per ft. must blow against 10.6 sq. ft. of area to produce such a force.

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Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Deflection of a cable from the catenary shape, however, will require much more force than the hanging weight, since both ends of the cable are fixed and it is already a convex curve. Therefore, in accordance with the law of increase of tension in a catenary with decrease of sag, which approaches the action of a toggle joint, the straightening out of other parts of the catenary cable, which must accompany bulges in the curve at any point, develop very high counter tension. A careful consideration of this matter will show that a catenary, under wind pressure and with small sag and high tension, is a very stable curve against deflection in the plane of the curve.

Furthermore, the swinging of cables will be largely "dead beat" on the wind (at least with transverse winds), and *will have no material pendulum or oscillatory movement.* It will be remembered that as a theoretic conclusion, pendulum action can occur only as the energy stored in momentum carries the moving body beyond a point of equilibrium against an elastic controlling force, thus paving the way for a return swing caused by the controlling force. The *velocity* of movement of the conductor in an actual span is relatively small, so that the kinetic energy stored in the moving cable cannot be sufficient to move it against gravity more than a few inches. No oscillatory movement of a few inches could be of serious importance in a transmission line. A velocity of one foot per sec. will cause a rise against gravity of only 0.02 ft. A velocity of 8 ft. per sec. would be required for the kinetic energy to be sufficient to raise the cable one foot against gravity. Thus it seems that due to wind across the line, there is little chance of conductors getting together horizontally.

Considering these principles in numerical relations, it may be assumed as an approximation that the danger of the deformation of the catenary and contact between cables is inversely proportional to the cable tension, other things being equal. It may be assumed also that it is directly proportional to the span, for obviously any given proportional deformation will give an actual displacement in feet proportional to the length of the span. Further, the displacing force will be proportional to the diameter of the cable representing the exposed surface.

The tension in any span taken as due to wind and weight will be proportional to the resultant of the wind and weights w, acting on the cable times the square of the span divided by the sag closely but not exactly.

The danger of contact would then be proportional so far as the above factors are concerned to

$$\text{Span} \cdot \frac{\text{Sag} \cdot \text{Diam.}}{w \cdot \text{Span}^2} = \text{Sag in per cent} \cdot \frac{\text{Diam.}}{w}$$

and might be written for preliminary purposes as

$$\text{horizontal spacing} = C \frac{\text{Diam.}}{w} \cdot \text{Sag in per cent where}$$

C is a constant.

The effect of cable weight is to give greater tension and hence is favorable; but its effect is already included in the formula. The effect of diameter would seem to be relatively unimportant because both the force restraining (tension) and the force causing deformation (wind puffs) are affected more or less alike by diameter. This mathematical expression will be further considered below.

Longitudinal wind will cause a deformation of the catenary in a vertical plane but so long as it is a horizontal wind it will not tend to cause contact.

The vertical component of any wind, whether transverse or longitudinal, tends to support the weight of the cable and thus reduce the tension which, in turn, tends to render contact in the span more likely and this is probably the principal cause of such trouble. If the uplift is sufficient to take all the weight off the wire, there is tension due only to transverse components of the wind. Under such conditions, minor forces will be largely free to move the conductor about in an accidental manner, rendering contact much more likely. For example, a gusty longitudinal wind blowing under a line up a concave, rising hillside, would be very favorable for trouble, for the wind would have an upward component which would take off the weight and tension on the wires and the irregular transverse components would be free to bring them together.

A 6.5-lb. per sq. ft. upward wind component will take all the weight off a No. 4 copper cable and a 15-lb. wind all the weight off a No. 0000 copper cable.

For all aluminum cable, the respective corresponding pressures are 2.0-lb. wind and 6.2-lb. wind, and for aluminum cable steel reinforced 2.8-lb. and 6.4-lb. A 2-lb. wind on cylindrical surfaces corresponds to a velocity of 27 mi. per hour actual, and 6-lb. to about 60 mi.

Causes of steady upward components of wind would be configuration of the ground or natural and artificial obstructions, such as trees, buildings, sign boards, gullies, etc. In any particular case, from an examination of the ground, a sufficiently correct inference as to the directions of air currents can no doubt usually be made.

The breaking off of ice and heavy wind in an adjacent span or other causes may produce a pulling of a certain short length of cable from one span into the next, but this will effect danger of contact in the span only indirectly, and whatever conditions might be set up to render the line safe in general against transverse wind conditions in the span would probably protect also against the effect of pulling from one span to another.

Similarly, transverse conductor swinging may be carried from one span to the next, but such swinging is

likely to be largely in synchronism for all conductors, unless in cases of very irregular ground configuration.

Apparently relatively short spans and very low stringing tension in the conductor tend to increase danger of contact, especially since it is highly probable that irregular wind and ground conditions do not exist over the whole length of any very long spans. This seems to be confirmed by reports of the behavior of extra long spans.

Side Hill Effect

A consideration of side hill effects,—that is, lines located on side hills,—is very interesting. So far as the main wind pressure is concerned, it must follow the slope of the ground, and will have an upward or a downward component affecting gravity. Puffs, or eddies, may occur in other directions. This means a steady uplift conponent or a downward component on the cable, on side hills, decreasing or increasing the effect of weight. This may greatly affect the magnitude and direction of the resultant loading on the cable on steep hill sides.

With copper cable, under a transverse wind, the angle of cable deflection from the vertical with an uphill wind will be somewhat, but not greatly, increased. With aluminum cable, even when steel reinforced, the uplift will sometimes exceed the weight in stiff winds causing a swing above the horizontal. This does not appear, however, to increase the risk of contact between cables, except where erratic variations in the strength of the wind may cause large variations in the vertical plane. The variations in a vertical plane, however, would tend to restrain deformations in the horizontal plane on account of the fixed length of the cable. It is highly probable that except for a very few exposed hill sides there will be a tendency for the wind to have a less velocity on hill sides than in the open. On the other hand certain formations of the terrain have the power, like some tapering river estuaries subject to tides, to cause an increase of velocity by deflections and reflections.

The most important aspect of this uplift by a component of the wind on the cable, however, is the possibility of the uplift raising the cable at the tower up against the under part of crossarm. It is possible that this may account for some unexplained flashovers at towers. A glance at the tables showing dead weight and wind pressures will evidence the importance of this matter for aluminum cable, especially for smaller cables. A dead weight hung on the end of an insulator string may be very useful on certain exposed steep hill sides.

Considering the different effects of various metals, it may be said that plain aluminum is the most dangerous, not because of its light weight so much as on account of its lack of strength and the resultant loose stringing.

As between copper and A. C. S. R., the preference is not so clear—the greater density of copper would be of advantage at least in so far as it gives greater tension, while the greater strength of the A. C. S. R., if used to advantage, leads to a higher cable tension and makes a less percentage sag and gives decidedly the stiffer catenary.

A downhill wind on the side hill will increase the *apparent* weight of the cable, and in the case of A. C. S. R., may more than double it; but this will not greatly increase the resultant stress on the conductor.

Wind Puffs and Eddies

No definite measure of wind irregularities seems feasible. We know that air in wind motion will act like water at the bottom of the sea, for air is substantially incompressible for variations of atmospheric pressure. Where a current meets an obstruction, it will be deflected to the side, or upward, with an increased pressure, but without increase of velocity. If a current, however, is directed into a funnel shaped cavity or recess, there may be a somewhat increased velocity. Air seems to be subject to cyclonic effects more than water, but they do not seem to be especially destructive to transmission lines. Presumably, the danger from these puffs and eddies is measurable by the factors already discussed above.

The only way to take account of expected irregular variations in wind action in the proposed formula is to make a purely arbitrary alteration in the factor C for any unusual conditions.

The only clear danger of contact in the span arises when, through deflection, by obstacles or a hollow formation of the surface of the ground, there is an upward turn of the wind, tending to raise the wire and thus give it slack within the span for accidental deflections.

Such obstacles and hollow surfaces must lie in direction along the line, so that a considerable length of span may be affected.

A typical example has been reported in a case where a transmission line paralleled the edge of a wood for a certain distance just outside. At this portion, the conductors were blown together in the span a number of times, presumably with the wind toward the wood. The obvious explanation would be the turning up of the wind strata blowing along the ground when they reached the wood, thus tending to raise up the conductors and allowing them to get together through the slack with no strong transverse pull to keep them all to one side.

The conclusion would seem to follow that each line should be gone over when installed for the purpose of locating wind obstructions or hollow shaped earth formation, and special precautions taken to prevent contact of wires wherever need appeared. It would be uneconomical to increase the width of structures over a whole line to meet a few determinable danger spots.

In the rare instances of contact in the span, known trouble has sometimes been due to other conditions than wind, which should be borne in mind. For example,

electromagnetic forces due to short-circuit currents have been known to produce contact of wires, presumably caused by reaction due to the sudden cutting off of the short-circuit current, since heavy current of itself tends to separate the wires. However, except in a few extreme cases of heavy wires close together, there is little likelihood of this happening, although an examination of the forces should be made in all close cases. A transverse magnetic force per foot of about 17 per cent of the weight of the conductor would be required to deflect the center of the span 10-deg. from the vertical. This cause of contact is not further considered in this discussion.

Since the same spacing must ordinarily be used throughout the line, the constant C should be determined by comparison with experience and should presumably be taken as applicable to the *normal tangent level span under Class "A"* loading conditions (or any other conditions that might be agreed upon) and it must contain factor of safety or margin enough to cover extra long spans and other variations. The apparent added risk from extra long spans is balanced partly by the much smaller chance of excessive air puffs and eddies on the large scale of the long span.

In choosing an actual formula, certain other considerations may be taken into account.

The jumping distance of the voltage is, of course, a factor to be taken directly.

The effect of the length of the insulator string appears to play little part in any of the above analysis and a long string would not seem to render contact more likely than a short string. Apparently antics in the middle of the span would not be greatly affected by the length of the insulator string. Nevertheless with our present imperfect knowledge of this subject, we would not be warranted in ignoring the length of insulator string. It may reasonably be assumed as an empirical formula that the horizontal spacing should include a part equal to the side deflection of the insulator string to the 30-deg. position. The normal spacing is certainly not likely to be reduced more than this due to the string. For pin type insulators this part becomes zero.

The above formula may then be set up as follows:

$$\text{Horizontal spacing} = C \cdot \text{Sag in per cent} \cdot \frac{\text{Diameter cable}}{\text{Class } A \text{ loading}} + D + \tfrac{1}{2} \cdot \text{Length of insulator string}$$

Where C = A constant chosen arbitrarily for each line to take account of the sort of metal of conductors, wind conditions, character of terrain, etc.

D = Jumping distance of line voltage—one foot for each 110 kv.

Sag in per cent is expressed without decimals, that is, 2 per cent is written "2."

If C be taken as 4 for copper cable and 3.5 for A. C. S. R. and their sags in the normal span respectively as 3.75 per cent and 3.25 per cent the spacings for No. 0000 cable would be as follows:

For 44 kv. Pin Type Insulators

No. 0000 Cu. No. 0000 A. C. S. R.

$$4 \cdot \frac{0.5275 \times 3.75}{0.927} + 0.4 \,, \quad 3.5 \cdot \frac{0.564 \times 3.25}{0.764} + 0.4$$

$$= 9.0 \text{ ft.} \qquad = 8.8 \text{ ft.}$$

For 66-kv. Suspension Insulators

ditto $+ 0.6 \tfrac{1}{2} \times 2.25 = 10.3$, ditto $+ 0.6 + \tfrac{1}{2} \times 2.25 = 10.1$

For 110-kv.

ditto $+ 1.0 + \tfrac{1}{2} \times 4 = 11.6$, ditto $+ 1.0 + \tfrac{1}{2} \times 4 = 11.4$

For 132-kv.

ditto $+ 1.2 + \tfrac{1}{2} \times 5 = 12.3$, ditto $+ 1.2 + \tfrac{1}{2} \times 5 = 12.1$

For 220-kv.

ditto $+ 2.0 + \tfrac{1}{2} \times 8.0 = 14.6$, ditto $+ 0.2 + \tfrac{1}{2} \times 8 = 14.4$

The above formula is the mathematical equivalent of the following:

In comparing two spans, *the horizontal spacing*, other conditions than those specified being equal,—

Should be twice as great in the first span when both have the same length, but the conductor in the first has one-half the tension of that in the second:

Should be twice as great in the first span when the first is twice as long and both have the same tension:

Should be the same in both when the first is twice as long and the second has half the tension:

Should be twice as great in the first when the diameter of the cable is twice as great,—the sag, span length, and loading per foot being the same in both:

Should be twice as great in the first when the loading is half,—the span length, the sag, and the diameter being the same.

In the formula tension and span length are the critical factors, one being as important as the other. The disadvantage of a long span can be made up by a higher tension and vice versa.

As instances of actual lines where an actual comparison can be made with this formula may be mentioned: (1) The Davis Bridge line of the New England Power Company with a two-circuit line of 12-ft. horizontal spacing on 110-kv. for No. 0000 copper wire; (2) A somewhat similar line of the Appalachian Power Company with 10-ft. spacing for 88 kv. for No. 0 copper conductor.

In conclusion it may be said that as a result of the various considerations already discussed, and of an examination of the proposed formula:

1. The safety against contact in the span depends apparently more upon tension in the cable and configuration of the ground than anything else.

2. The most dangerous conditions are probably those

in which the general wind velocity is not too high, this signifying low conductor tension, and is more or less parallel to the line, so that neither cable is blown far to either side, and in which there is an obstacle causing a local upward turn in the wind. The conditions will be worse in short spans and with small cables and large sags.

3. The cable conditions on side hills deserve much more consideration than they usually get.

4. The advantage of copper over A. C. S. R. or A. C. S. R. over copper, if either can be established, should be taken into account in the arbitrary constant C, as should also any variations of the terrain making the general conditions of any one line better or worse than normal.

The author has made considerable effort to locate examples of contact of horizontally spaced cables in actual service, where the conditions are known, for the purpose of selecting a constant for the formula derived above, but very few such cases have been discovered, although some 30 or more of the engineers in this country and Canada, with the best opportunity to know of such experiences, have been consulted. The following letters and extracts describe a few very interesting and pertinent cases and seem definitely to support the conclusions of the paper.

"THE MONTANA POWER COMPANY
Butte, Montana

August 2nd, 1927.

Mr. Percy H. Thomas,
120 Broadway,
New York, N. Y.
Dear Sir:

Case 1. We have a 60-mi., 100-kv. line built-on steel towers passing through the north end of the Tobaccoroot Mountains. The line is No. 0 hard drawn seven wire copper 10-ft., 6-in. horizontal spacing, 36-in. insulators strung at 1200 lb. tension at 32 deg. fahr., with 2⅜-in. Siemens Martin ground wires midway between phase wires and four feet above the phase wire plane. Ground wire was strung at 1500 lb. at 32 deg. fahr. This line had several spans ranging from 1000 to 1200 ft. crossing valleys and gulches more or less at right angles to the line, where the wind was apt to be severe and where it no doubt would strike one end of the span more than the other end and where it might have had a vertical component of at least 30 deg. to the horizontal. Many of these spans suffered short circuits during wind storms so that it was necessary to anchor the wires in midspan with hold-down anchors so run as to spread the two outside wires away from the middle wire at mid-span.

Case 2. We have a considerable length of 50-kv. pin type line consisting of three-phase wires and a ground wire all on the same crossarm at a uniform spacing of 42 inches. The phase conductors are each composed of three No. 8 wires, stranded, and the ground wire is the same size of steel. The wire was strung at 400 lb., 70 deg. fahr., and has developed several contacts on spans of 400 to 430 ft., crossing gullies in a rolling prairie country where the wind had an opportunity to cause eddies and other disturbances.

Case 3. We have personally observed a 1000-ft. span constructed similarly to Case 1 above and located at the top of a mountain ridge where a canyon led up to the top. Irregular blasts of wind coming over the canyon would cause the wires to deflect and in some cases this deflection would get sufficiently out of phase so that one wire would be practically in a vertical plane when the next wire was at nearly maximum horizontal deflection. We also observed that even under light wind, say, ten miles per hour, there were often irregular ripples running lengthwise over the wires. These ripples however, were not of great magnitude and could not have had anything to do with cause of contact between phases. The maximum ripple probably was not more than 18 in. Our observation leads to the conclusion that wires can be caused to swing out of synchronism to a considerable extent but we do not think it possible for two wires to swing in opposite directions at the same time under heavy wind conditions. Obviously, the greater danger of contact is in narrow valleys, or other broken topography, where the wind velocity is often excessive and also very turbulent.

As opposed to the cases of contact noted above, we have had spans 3200 ft. long at 22 ft. spacing strung at about 1200 lb. for ⅜-in. steel at 70 deg. fahr. over a straight smooth river channel, which were never in contact during 10 years of experience.

Yours very truly,
(Signed) A. C. Pratt."

NOTE: The 3200-ft. span described in the last paragraph would have apparently, a sag of approximately 15 per cent under the conditions of Class A loading. The formula would give for a copper conductor of the same size a horizontal spacing of over 40 ft. for a 110-kv. circuit, while no trouble was actually experienced with a 22-ft. spacing.

From another engineer there is a report that after experiencing trouble with all aluminum 3/0 and 4/0 cables on 500 ft. spans, with wires horizontally spaced 8 ft., with insulator string approximately 4 ft. long, this trouble being due to getting together of conductors in the span under the influence of wind, entire elimination of the trouble was obtained by the substitution of aluminum steel cable, 266,800 cir. mil, and 336,400 cir. mil, this being over a considerable length of line.

NOTE: If the sag with the aluminum steel cable be taken at 2 per cent, the formula would call for a 10-ft. spacing while no contacts have been experienced in many years with an actual 8-ft. spacing.

Extracts from report by Mr. V. M. McDonald, Supt., Transmission, Public Service Company of Colorado, received August 15th, 1927.

* * * * *

Span length, 400 ft.

Sag, 11½ ft.

Horizontal spacing, 10 ft. 6 in.

Voltage, 90,000.

Length of insulator string, 32 in.

Size and material of conductor, No. 1 hemp center copper strand.

Tension, 1150 lb.

Approximate wind velocity, (mi. per hr.), 85 at time of trouble.

Direction of wind with respect to conductor, right angles.

No sleet.

Location, side hill and nose slope.

When wires came together, circuit breaker tripped, conductor pitted.

This is the only known case where conductor came close enough to cause an arc. Wind was at right angles to line. Hillside deflected wind to an upcast underline that raised cables and they fell close enough to cause trouble.

We have several arcs between conductors on 44-kv., 4-ft. spacing triangle, due to burning weeds along railroad right-of-way.

NOTE: The last paragraph, while of value, does not relate to the swinging of conductors.

It is hoped that engineers interested in this matter will offer discussion on the above analysis, and will contribute any pertinent data they may have so that as much as possible may be assembled for the benefit of any who may have such horizontal constructions to install.

Discussion

M. G. Lloyd: While Mr. Thomas has not attempted to give a complete analysis, he certainly has given us much food for thought on this problem. There is one thing I don't believe is made entirely clear. The tension in the conductor depends upon the loading condition. In the problems he has worked out, Mr. Thomas has taken the diameter of the wire bare, apparently, but has taken the loading with the ice on it. In other words, he has not taken the two constants that correspond one with the other. The tension in the wire, which is involved in deriving his formula, will depend, of course, on whether or not the wire is loaded.

From the discussion it seems to be clear that he considers the greatest danger of contact between the wires to be at the time of a wind with a vertical component acting upon the wire without ice upon it, and that seems a reasonable assumption as being the most dangerous condition. In working out the problems, however, he has taken the loading including ice on the wire, so that it doesn't seem to me his two conditions of diameter and of loading correspond to one another. I should think they both ought to be taken for the same condition.

Furthermore, in working out the examples on the fourth page, the author has assumed a definite percentage sag (percentage of span length). That percentage in practise, of course, varies with the span length and the values chosen would apply approximately for only a small range of span lengths. In the case of copper, for instance, where he takes the sag as 3.75 per cent of the span length, that would apply to a span length of, perhaps, 900 ft. or something in the neighborhood of that. For other span lengths that percentage would not be applicable and consequently, the results worked out would not seem to be applicable. He has not stated here what span length he is talking about. In working out these examples, if an entirely different span length is used, one gets results which are not at all comparable with practical values. For instance, if we take a very long span, the separations that are obtained by this formula, using that percentage of sag, come out in some cases entirely different from what would be considered practical values.

This formula, it is to be noted, brings in the first power of the sag as an element of the separation. I think experience has shown that more practical results are obtained by bringing in the square root of the sag rather than the first power. It is not clear just how that would be justified on theoretical grounds, as I do not see any imperfection in the author's reasoning to bring it in in the way that he does, but his formula will not be found very widely applicable when one considers a big variety of span lengths and the percentage sags corresponding to them.

In the statement on the fourth page, as to the application of the formula, the author says, "In comparing two spans, the horizontal spacing, other conditions than those specified being equal—," and he gives a list of a number of different conditions. As a matter of fact, you can't vary the things he mentions without varying the other quantities. It isn't a feasible, practical case to keep the other values constant when you vary those that he mentions.

For instance, in the first three cases, varying the tension, for instance, without varying the span length, the sag also will vary necessarily. You can't help but vary it or else vary the size of the conductor, which is another variable. That is true also if you keep the tension the same but vary the span lengths, which is the second case, or if you vary the tension and span length together, which is the third case. In the fourth and fifth cases, changing the diameter with the sag, span length, and loading the same, you will invariably change the tension. Of course, the tension doesn't appear explicitly in this formula, so that that does represent a case which is a practical one and the relations will be just as he has stated.

In the conclusions the author makes the statement, "The conditions will be worse in short spans and with small cables and large sags." I think in practise that doesn't work out because when you have the short spans you invariably have the small sags and probably high tension and you are consequently not likely to have trouble with short spans from this cause.

In the examples given in the letter quoted, the span lengths seem to run up to values that are not extremely high, but a thousand feet or so. I am sorry that in these examples of actual contacts that are cited there is nothing said about what the actual sag of these particular conductors was. If that could be given it would help to form some picture of the condition where these contacts have occurred.

On the fourth page where the values of actual separations of the Davis Bridge line and the Appalachian Power Company are compared to what is worked out in the formula, the sags do not appear to be given, so that it is difficult to determine how well they do fit the formula. It is possible that the percentage sag used in the examples worked out at the top of the page fit these particular cases that are mentioned but the data, unfortunately, are not given to check up on that point.

Transmission Experience of the Public Service Company of Colorado

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Associate, A. I. E. E

and

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Synopsis.—*The 100,000-volt transmission lines of the Public Service Company of Colorado, which were completed in 1909, extended from the Shoshone hydro plant on the Colorado River across the Continental Divide to Denver and represent pioneering in high-voltage transmission at high altitudes. This combination of factors, coupled with a rapid expansion of the whole system in recent years called for the satisfactory solution of many problems. The paper describes the system in a general way, and outlines some of the more salient operating difficulties that have arisen from time to time as well as their remedies. Brief mention is also made of the method of load dispatching.*

* * * * *

Introduction

THE purpose of this paper is to submit the results of several years of operating experience of the high-voltage network of the Public Service Company of Colorado. Every transmission system has its own inherent mechanical and electrical features which are governed primarily by the amount of power to be transmitted, size of conductors, line voltage, spacing of conductors and towers, ratio of resistance and reactance and climatic conditions. Methods practised in load dispatching and the means of communication between various points on the system will vary for many reasons, depending largely upon local conditions and the best judgment of the engineers in charge. Furthermore, when any new problem in transmission engineering is encountered, or any change is contemplated, for the betterment of the service to be rendered it is always helpful to learn of the experiences of others who have been operating transmission systems.

A part of the transmission lines included in the present network operated by the company has been in continuous service for 20 years. Two years following this initial construction, the line was extended to a total length of 153.5 mi., from the Shoshone hydro plant on the Colorado River near Glenwood Springs across the Continental Divide to Denver, and from Denver to the Boulder hydro plant. Other sections of the network have been constructed during the past four years. With the exception of the transformers at the Shoshone hydro plant which were rebuilt last year, all of the original transformers and oil circuit breakers are still in service. This not only represents pioneering in the field of high-voltage transmission, but also progress in the art of design, construction, and operation. It is hoped that the data herein submitted will add to the information now available on such operating experience; also, that it may prove to be of some value to those having similar operating and maintenance problems.

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Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Description of System

The company serves the electric lighting and power requirements of practically all of the central, north central, and northeastern portions of Colorado. The area served covers approximately 750 sq. mi. and includes about 116,300 customers.

The high-voltage system comprises a total of 518 mi. of line at altitudes ranging from 5280 ft. to 13,700 ft. above sea level with 217 mi. of line operated at 100,000 volts and 301 mi. of line at 44,000 volts. The properties are segregated into what is known as the central system and the outside system, there being no means at present of interconnecting these two groups. Transmission in the central system is over 217 mi. of line at 100,000 volts and 181 mi. of 44,000 volts, and in the outside system transmission is all at 44,000 volts over 120 mi. of line. The map in Fig. 1 shows the territory served by both systems, as well as the location of the generating plants supplying these two principal transmission networks.

The generating plants connected to the central system, their capacity, and type of motive power are listed in Table I, while those of the outside system are listed in Table II. Since the outside system comprises only a small portion of the total properties operated by the company, the remaining material submitted in this paper will be confined entirely to the 100,000-volt transmission lines of the central system, a simplified diagram of which is given in Fig. 2.

The transformers supplying the 100,000-volt loop at Boulder Canyon and Valmont are star-connected, with the neutral solidly grounded. The step-down transformers at the Denver Terminal are delta-connected, on both high- and low-tension windings. The 100,000-volt transformers at Shoshone have been rewound recently for star operation on the high-voltage side, and the neutral has been solidly grounded. This connection has not yet been in service through a lightning season, and no data on the effect of this connection on flashovers are available. It has, however, greatly improved relay operation.

The 100,000-volt loop is equipped with impedance type protective relays, which have given correct sec-

tionalization for about 95 per cent of the flashovers. Until recently, flashovers on the Shoshone line have been cleared by manually lowering generator voltage. Automatic equipment was installed in October, 1927, for lowering generator voltage by inserting a large block of resistance in the generator field circuit.

The switching center of the central system is the Denver terminal substation, located two miles within the city limits of Denver. Three 100,000-volt lines converge there, and 60,000 kv-a. in transformer capacity is provided for supplying 13-kv. city feeders. The system operator and dispatching office are located at this substation. Private telegraph and telephone, and leased telephone lines are provided for communication with all parts of the central system.

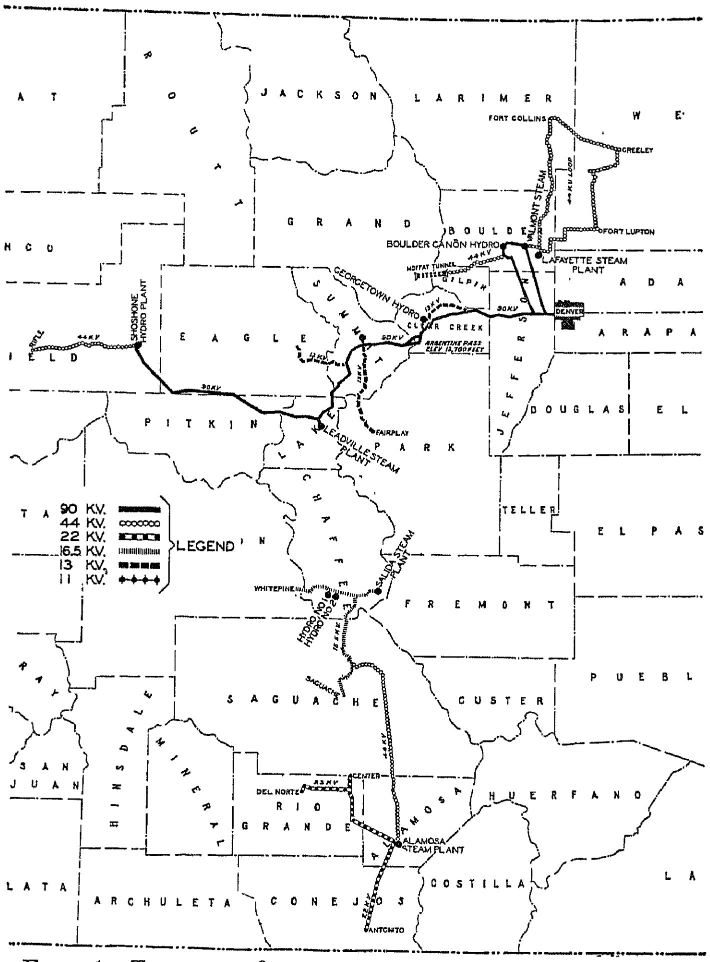


FIG. 1—TERRITORY SERVED BY THE PUBLIC SERVICE COMPANY OF COLORADO

ALTITUDE—WEATHER CONDITIONS

The 100,000-volt line which crosses the Continental Divide presents a most difficult task of maintaining a high degree of continuous service. Reference to the profile of this line as shown in Fig. 3 discloses that the line originates at an altitude of approximately 6000 ft. at the Shoshone hydro plant; then traverses the Rocky Mountains, negotiating three passes—Hagerman at 12,000 ft., Freemont at 11,500 ft., and Argentine at 13,700 ft., thence to the Denver Terminal at 5280 ft. above sea level.

Shortly following the completion of this line, many interesting experiments were conducted and some of the results have appeared in Institute papers. The weather conditions during the winter season are very severe, making it difficult to secure all the operating data which often would be desired in cases of trouble. At the higher altitudes in the fall and spring there is an abundance of moist winds, whereas in the winter temperatures as low as 52 deg. below zero fahr. have been recorded. The maximum measured wind velocity so far reported is 165 mi. per hour. These conditions, combined with the heavy snows, make certain sections of the line almost inaccessible for a period of time, which means that the line must be thoroughly dependable from both the electrical and mechanical standpoint.

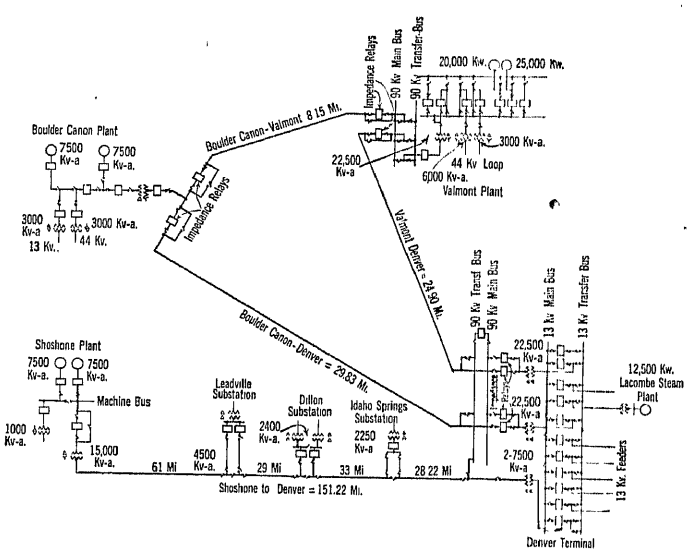


FIG. 2—SIMPLIFIED DIAGRAM OF THE 100-KV. LINES OF THE PUBLIC SERVICE COMPANY OF COLORADO

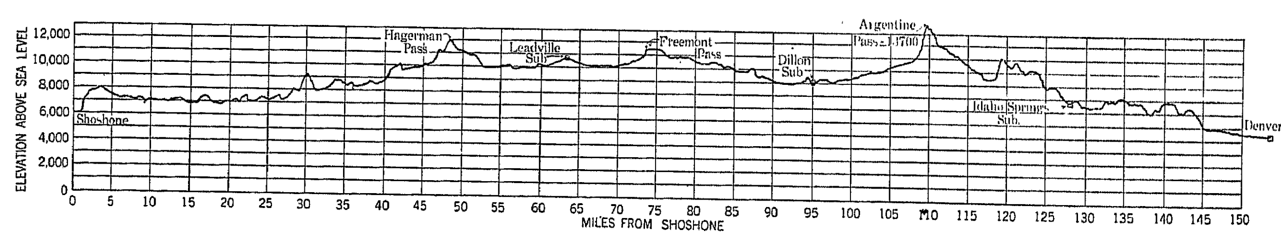


FIG. 3—PROFILE OF TRANSMISSION LINE, SHOSHONE TO DENVER; DENVER TO BOULDER

There are times when the winds are heavy-laden with moisture which freezes as it strikes the cold surfaces of the towers and conductors. This frost formation which usually builds out against the wind has been found to cover the conductors with an over-all dimension of 12 in., with still greater masses on the towers. Frost formations measuring 2 to 2½ ft. in thickness have been observed on the towers but so far there has been no failure of towers on account of this loading. Fig. 4 shows an interesting view of this ice formation; also

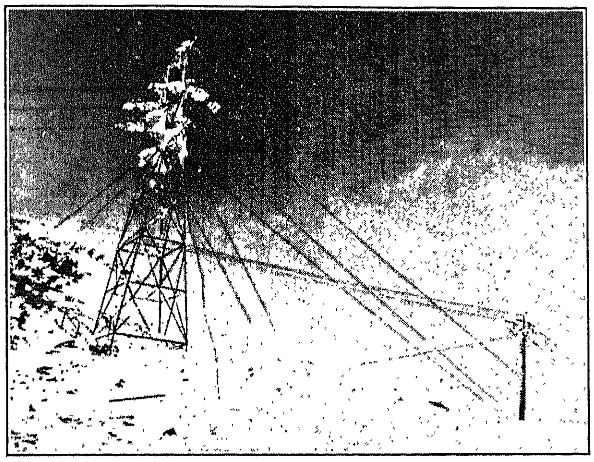


FIG. 4—TOWER ON ARGENTINE PASS. ALTITUDE 13,700 FT.

the method of holding the jumpers in place against the high wind velocity. This particular tower stands at the top of Argentine Pass.

One of the important factors taken into account in locating the tower line were snow and rock slides. Whenever it appeared unlikely to avoid these slides, heavy cribs were built around the towers to prevent their destruction. Fig. 5 shows the method adopted to protect the towers from such slides. The cribs are constructed V-shape and on the up-hill side of the tower, the intention being to split the slide. This type of protection, illustrated in Fig. 5, is constructed of heavy steel section securely anchored and filled with rock. During the nearly 20 years that the lines have been in operation, only ten tower failures have occurred attributable to slides. Of this number, one failure resulted in both the protecting crib and its tower being carried away by the slide. Landslides also have been the cause of several tower failures.

Considerable lightning is encountered on this line, covering an average period of 130 days per year. Many statements are made to the effect that insulation is the foundation of the electric power system; and true it is; yet any line exposed to storms, lightning, and slides, as previously mentioned, calls for a high degree of sturdiness in both electrical and mechanical design. The line across the Continental Divide has been in operation sufficiently long to enable a satisfactory solution to most of the mechanical problems in maintenance, but the problem of protection against lightning is still a very difficult one to master reasonably.

TABLE I.
GENERATING PLANTS—CENTRAL SYSTEM

Location	Rated kw. at 0.8 p. f.	No. of units	Motive power
Shoshone	14,400	2	Water
Boulder Canyon	14,400	2	Water
Georgetown	900	2	Water
Leadville	1,925	2	Steam
Lafayette	6,000	4	Steam
Denver (West Plant)	9,250	4	Steam
Denver (Lacombe Plant)	16,500	3	Steam
Valmont	45,000	2	Steam

TABLE II
GENERATING PLANTS—OUTSIDE SYSTEMS

Location	Rated kw. at 0.8 p. f.	No. of units	Motive power
Cheyenne	4,000	4	Steam
Sterling	2,250	3	Steam
Alamosa	1,400	2	Steam
Salida	700	2	Steam
Salida	1,200	5	Water

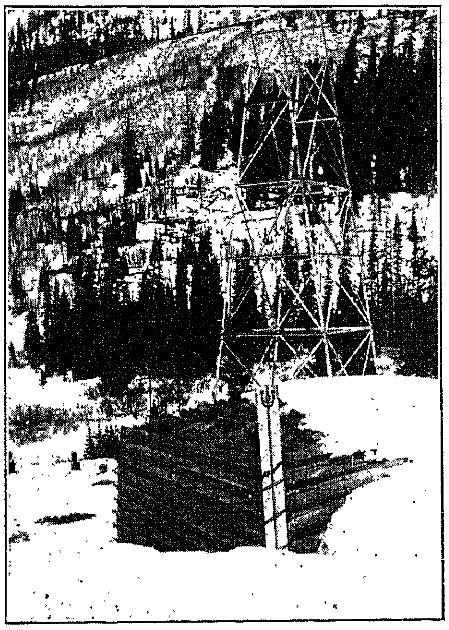


FIG. 5—CRIB PROTECTING TOWER FROM SNOW AND ROCK SLIDES

LINE INSULATION

The original insulation was four Hewlett disk insulators on both dead-end and suspension strings with a 7½-in. spacing of disks on the dead-end and 6-in. spacing on the suspension strings. The ratio of dead-ends to suspensions was about one to fifteen. Two ¼-in. steel ground wires were put up for protection. Many difficulties were encountered during the first year of operation, principally on account of the lines being under-insulated and on account of mechanical failures of the ground wires. During the following year, the ground wires were removed, and a fifth disk was added to all dead-ends. This measure showed some improvement in service. During the following year,

arc points were placed on both ends of all strings to provide a flashover path which did not destroy insulators. However, they do not reduce the number of outages caused by lightning.

In 1916, it was decided that the flashovers per annum were still too numerous, whereupon a fifth disk was added to all suspension strings and a sixth disk to all dead-ends. This reduced the number of flashovers approximately 75 per cent.

New 100-Kv. Lines

The Valmont-Denver line and the Valmont-Boulder line (see Fig. 2) were built during 1924, and placed in service during December of that year, which also marked the completion of the first unit of the new Valmont steam plant. These two lines tie in the plant with the Denver Terminal and with the Boulder Canyon hydro plant. American Bridge Company towers were purchased for both lines and designed for single circuit horizontal conductor spacing on the Valmont-Boulder tie, (see Fig. 6), while twin circuit vertical conductor spacing is used on the Valmont-Denver tie. Only one circuit was strung on the latter tie, and the second circuit will be added when the growth in load reaches such a point as to demand it.

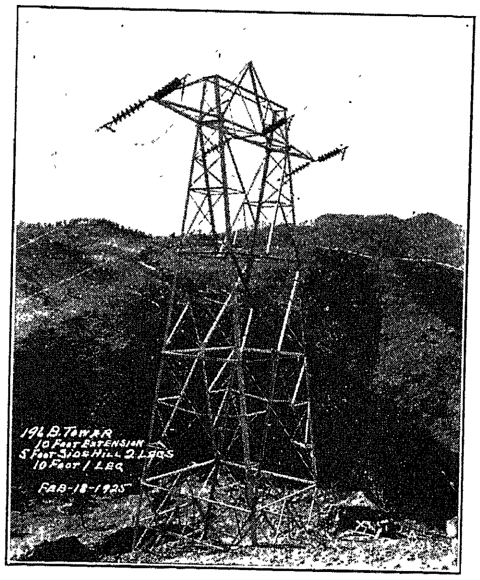


Fig. 6—Type of Tower used on Valmont—Boulder Line

High mechanical strength, 336,000-cir. mil, A.C.S.R. conductors are used on both tie lines, the cable being made up of 30 strands of aluminum 0.1059 in. in diameter and 7 strands of steel 0.1059 in. in diameter. All suspension strings consist of seven No. 25622 O-B insulators spaced 4¾ in., and all dead-end strings consist of seven No. 26240 O-B insulators spaced 7 in. Arc points were initially placed on suspension clamps and at dead-end points on all strings, hoping to avoid breakage of upper disks by flashovers. Fig. 7 shows a typical failure of upper disk, and Fig. 8 shows type of upper arc points which are being installed.

Ground Wires

Before going into a discussion of the interruptions to service on the 100,000-volt lines, it would be well to review the company's experience with ground wires. In the original design of the Shoshone-Denver and the Boulder-Denver lines, two ground wires were incorporated in an effort to avoid lightning troubles. These ground wires were soon abandoned and taken down on account of mechanical difficulties as previously mentioned. All towers on the new tie lines to the Valmont plant are so constructed that a ground wire may be added readily, but to date this has not been done.

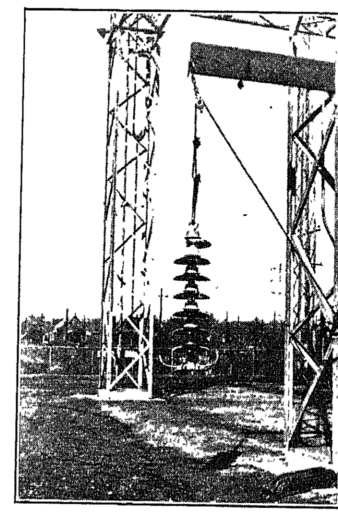


Fig. 7—Upper Disk Failure when not Protected by Arc Points

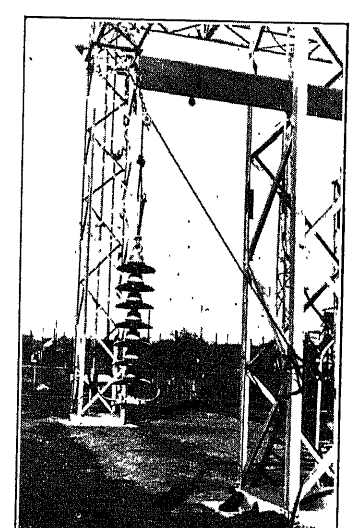


Fig. 8—Type of Upper Arc Points being Installed

The lines from the Shoshone and Boulder hydro plants and the Valmont steam plant converge at a point about four miles west of Denver. From the Dry Creek substation, 2½ miles west of the terminal, the circuits from the Boulder and Valmont plants are

carried on a double circuit tower line, the construction of which is illustrated in Fig. 16; while the Shoshone circuit is brought the same distance over a single circuit H-frame wood pole line, all on a common right-of-way. This double circuit of 2½ miles in length has been protected with a ground wire through two lightning seasons, with the result that there has been no insulator breakage on account of flashovers, and it is believed that there have been no flashovers during this period on this particular section.

Types of Towers

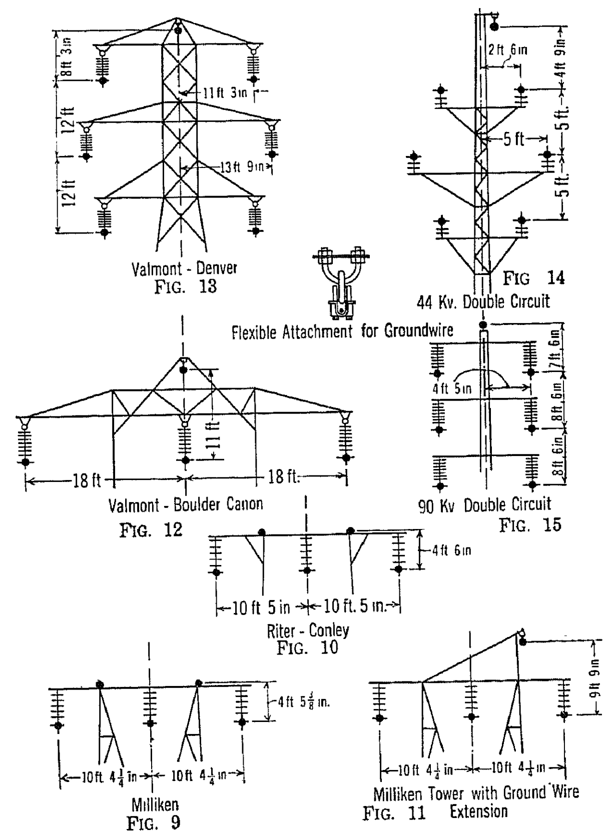
The Shoshone and Boulder Canyon lines were built on two types of towers, as indicated in Figs. 9 and 10. The tower shown in Fig. 10 was originally intended for double circuit use, with the second circuit directly below the upper circuit. This arrangement was found impracticable, and the lower arm was removed. Both of these towers were originally equipped for two ground wires, with clamps located at the connection of tower legs and the upper arm. Spacing was inadequate and ground wire failures were frequent, so they were taken down shortly after construction. Fig. 11 shows an extension recently added for carrying a ground wire over a portion of the Boulder line. The ground wire is flexibly supported in a standard conductor suspension clamp. The tower shown in Fig. 10, with a height of 50 ft. weighs 3600 lb. Fig. 9, 44 ft. high, weighs 1980 lb. In the Boulder Canyon–Valmont line built in 1924, the tower shown in Fig. 12 was used. It weighs 6000 lb., with a height on top of insulator string of 41 ft. The Valmont-Denver towers, Fig. 13, double circuit, built in the same year, weigh 7600 lb.

The tower shown in Fig. 9 appears to be very light and of flimsy construction, and guys are used on many towers. However, few tower failures have occurred. The somewhat flexible construction of these towers has probably relieved the stresses on them, and has permitted the guys to take some stress before tower members failed.

The steel poles, shown in Figs. 14 and 15, were used where right-of-way difficulties required narrow base construction.

Interruptions

Such information as has been recorded which may enable an analysis of the causes of interruptions is summarized in Table III. The data on outages have not been recorded with the degree of completeness which might be followed were a special study to be conducted on this phase of operation. The number of broken



FIGS. 9—15

TABLE III
SUMMARY OF INTERRUPTIONS

Line—Year	Spacing	Lightning	Operating error	Plant or sub-station trouble	Secon-dary trouble	Jumper off	Slides	Wind	Rifle shooting	Birds	Unknown	Total line	Total year	Broken con-ductors
1925														
Shoshone-Denver....	Flat	49	0	6	1	0	1	8	0	0	4	69		6
Boulder-Denver......	Flat	6	0	1	1	0	0	0	0	0	0	8		1
Valmont-Denver.....	Vert.	6	1	0	0	0	0	0	0	0	1	8		0
Valmont-Boulder	Flat	0	0	0	0	0	0	0	0	0	0	0	85	0
1926														
Shoshone-Denver....	Flat	46	1	3	4	1	0	1	0	0	7	63		2
Boulder-Denver......	Flat	10	0	1	0	0	0	0	0	1	1	13		0
Valmont-Denver.....	Vert.	14	0	0	0	0	0	0	0	0	0	14		0
Valmont-Boulder	Flat	0	0	1	0	0	0	0	0	0	0	1	91	0
1927														
Shoshone-Denver....	Flat	35	0	2	5	3	5	5	1	0	4	60		5
Boulder-Denver......	Flat	8	0	0	0	1	0	3	0	0	0	12		1
Valmont-Denver.....	Vert.	11	0	0	0	1	0	0	0	1	2	15		0
Valmont-Boulder....	Flat	2	0	0	0	0	0	0	0	0	0	2	89	1

conductors as given in the last column of Table III for each line during each year, are included in their proper places under other headings in the table. In some instances the failure was attributed to wind, while in other instances, the cause was not definitely apparent.

The prevalence of thunderstorms in the mountain regions causes many interruptions on account of lightning. The number of outages from this source amounted to 71.8 per cent in 1925; 77.8 per cent in 1926; and 62.9 per cent in 1927. The lightning report of the company for 1927 gives a total of 228 thunderstorms accompanied by a quantity of lightning, the first reported on March 30th, and the last reported on October 12th. During this period there were 56 trip-outs, and a total of 91 insulators had to be changed on account of disks being shattered.

One interesting relation which is evidenced by the summarized data on lightning as given in Table IV, is the comparison of the "miles of circuit per trip-out per lightning season" for the several 100-kv. lines. Bearing in mind the fact that these circuits are not protected by a ground wire except for the 2½ mi. of vertical-spacing double circuit from the Dry Creek substation into the Denver Terminal, the conclusion to be drawn is that flat construction without ground wire is least disturbed by thunderstorms. Following the observations which have been made to date on this particular phase of operation, the company decided that a ground wire properly installed is an essential adjunct to the system, and is proceeding with its construction, due attention being given to its material, location, method of attachment, and stringing tension.

TABLE IV
SUMMARIZED LIGHTNING REPORT

Line	No. times lightning reported	No. times breakers opened	No. insulators damaged by lightning	Miles ckt. per trip-out per season
		1925		
Shoshone-Denver	106	49	33	3.1
Boulder-Denver	44	6	14	5.0
Valmont-Denver	25	6	6	4.6
Valmont-Boulder	8	0	5	—
Total.......	183	61	58	
First lightning reported April 6th; last reported November 13th.				
		1926		
Shoshone-Denver	153	46	19	3.3
Boulder-Denver	61	10	12	3.0
Valmont-Denver	23	14	10	1.9
Valmont-Boulder	18	0	9	—
Total	255	70	50	
First lightning reported March 20th; last reported October 4th.				
		1927		
Shoshone-Denver	130	35	38	4.6
Boulder-Denver	47	8	20	3.7
Valmont-Denver	25	11	23	2.5
Valmont-Boulder	26	2	10	4.0
Total.......	228	56	91	
First lightning reported March 30th; last reported October 12th.				

The ground wire is flexibly suspended from "U" bolts or eyes in a standard conductor clamp and in a position where it is free to swing. In other words, instead of treating it merely as a doubtful appendix to the circuit, it is receiving the same careful consideration as though it were one of the main conductors.

In all but two cases where insulator damage occurred on the Valmont-Denver line as a result of lightning, the damage was confined to the string supporting the top conductor. This is in line with results to be expected on vertical type construction.

Table III indicates that substation troubles have somewhat frequently affected transmission line operation. Occasional 100-kv. bus flashovers occur in the indoor substations, although the busses are separated by twice the flashover distance between line insulator arc points. These troubles appear to be most frequent in the substations at Dillon and Leadville, which are

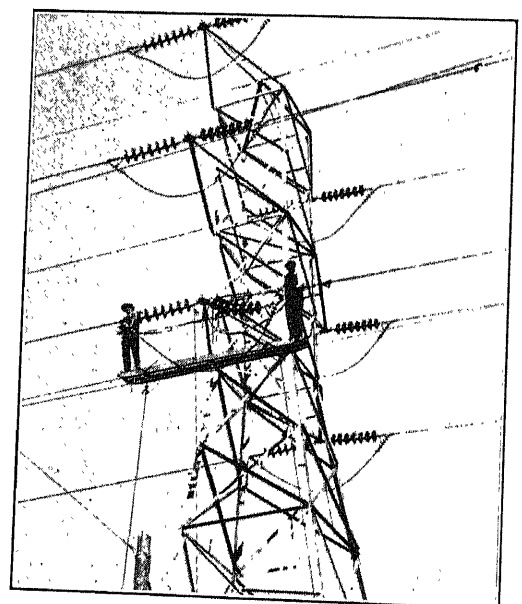


FIG. 16—TYPE OF DOUBLE-CIRCUIT TOWER

approximately 9500 and 10,500 ft. above sea level respectively. Grounding the line neutral seems to have largely eliminated this trouble.

INSULATOR FAILURES

When the new lines were built, seven close-spaced disks were used in suspension, with the expectation that cascading on flashovers would be avoided. Arc points were provided on the suspension clamp to avoid burning of the conductor. Operating experience indicates that practically all flashovers damage one or more insulator disks at the top of strings. A theory has been proposed by the insulator manufacturers that the swinging bracket used for mechanical reasons in supporting suspension strings causes a detrimental distribution of electrostatic flux. Upper arc points are being installed at all points to protect the insulators from flashover arcs.

It is of interest to note that in the 50 flashovers which have occurred on the new lines, in all but one case it has been possible to restore service immediately without repair or insulator replacements. In the one case excepted, insulator hardware was burned through on account of a relay failure, and the conductor was dropped. This string is shown in Fig. 17.

Conductor Failures

The failure of power conductors and ground wires as a result of vibration is a subject which has received considerable attention in recent years. Efforts have been made to determine those factors which contribute to destructive vibration and valuable data have

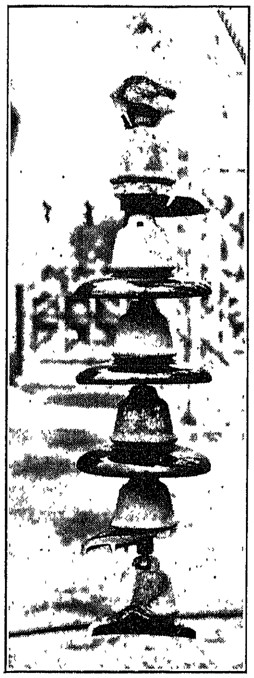


Fig. 17—Insulator Hardware Burned Through

been assembled. Within its lifetime of operation the Public Service Company of Colorado has experienced approximately 200 conductor failures attributed to various causes. The majority of these cases of trouble occurred in the early years of operation and repetition was prevented by the use of a flexible joint between the conductor and the insulator for suspension type construction and at the towers for dead-ends.

One interesting and peculiar type of conductor break began to develop in 1921 for the first time and has been showing up since at an increasing rate. Horizontal spacing is used on the Shoshone-Denver and on the Boulder-Denver lines, these lines having been constructed in 1909. All conductors as initially installed consisted of six copper strands with hemp center. Referring to the profile in Fig. 3, No. 1/0 conductor was strung from Shoshone to Leadville; No. 1 conductor from Leadville to Dillon; No. 1/0 conductor from Dillon to Denver, and No. 1 conductor from Boulder hydro plant to Denver with a tension of 1250 lb. at 60 deg. fahr. Steel towers are used the full length of these lines, with a normal span length of 700 ft., a minimum of 300 ft., and a maximum of 2700 ft. The general direction of the wind is parallel to the Shoshone-Denver line and at right angles to the Boulder-Denver line.

The probable phenomenon surrounding the type of failure which began to show up on the Boulder-Denver line in 1921, and not until in the spring of 1927 on the Shoshone-Denver line, has aroused much concern for the reason that it has been necessary to replace 11.4 line mi. of conductor to date on the Boulder-Denver line on account of failure of individual strands. A close examination of the breaks in the individual strands reveals that some strands fail from crystallization, some from elongation, and some from an apparent crystallization. If the length of the conductor between two points is divided roughly into thirds, these breaks occur most frequently in the third of the span length next each point of support, and very rarely in the middle third. The breaks in a single strand are found to occur from ½ in. to 4 in. apart, while these breaks appear to be in a stage of development along the conductor grouped at intervals of 6 in. to 6 ft. apart.

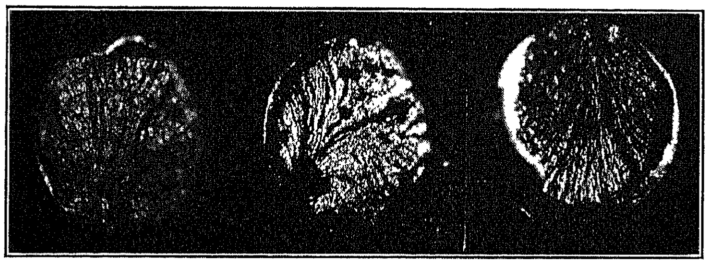


Fig. 18 Fig. 19 Fig. 20

Strand Failures

All but one of these conductor failures have occurred on the Boulder-Denver line and in that section of the line which traverses what is known as the Rocky Flats, just north of the city of Golden, where the prevailing severe winds are at right angles to the transmission line. From observation, it is found that in addition to the swinging of an entire span length of one conductor, there are segmental vibrations set up. These segmental vibrations promote crystallization, which in time develops a slight fissure in the strand next to the hemp center. Then there is a possible electrolytic action set up following the creation of the fissure, the metal being conducted through a film of moisture and deposited on the hemp center. This line of reasoning does not always appear to be borne out by facts; for while there is a noticeable deposit of copper on the hemp center in some instances, there are other instances in which the hemp is very badly disintegrated with no sign of copper deposit and still others where the hemp is in a high state of preservation with no sign of copper deposit. Another thought which has been advanced is that the wire as received from the mills contains slight flaws which

progressed under vibrational stress. Neither theory seems to provide a satisfactory answer.

The appearance of a strand failure enlarged to approximately 20 diameters may be seen in Figs. 18, 19, and 20. These particular ones are three of a total of four strands in a conductor break having the same characteristic appearance, while the other two strands of the conductor failed as a result of elongation with a slight amount of burning as the conductor finally

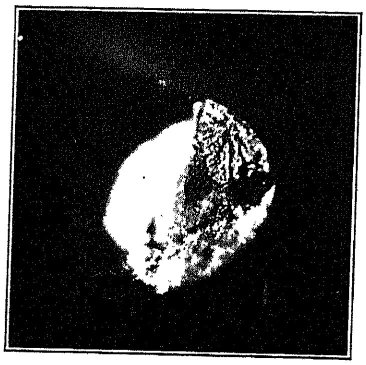


FIG. 21—STRAND FLAW DISCOVERED AFTER CONDUCTOR WAS REMOVED FROM LINE

parted. All six strands parted within a distance of 11 in. along the conductor. It will be noted that a very definite crater exists, partly as a result of the disappearance of metal, and partly on account of the necking down of the small amount of metal left around the periphery of the strand. These three illustrations are typical of all those investigated where the fissure had progressed nearly all the way across the strand.

Fig. 21 shows an enlargement of a break completed

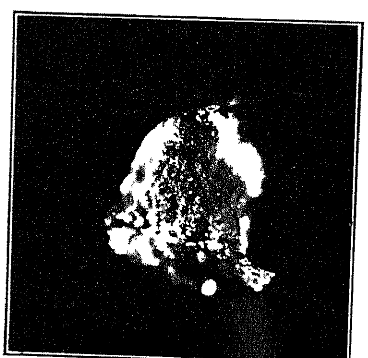


FIG. 22—STRAND FAILURE PRODUCED MECHANICALLY

by hand. As the strand was unwound from the conductor it parted with less effort than the breaking of a thin toothpick. In other words, it virtually fell apart, so high was the degree of disintegration. The break was a little more uneven than in the three preceding illustrations, and could not be focused uniformly. It may be seen, however, that the fissure had progressed more than a quarter of the way across the strand with the same characteristic stream lines converging at a point of discharge as in the other strands, and that the process of creating the defect is in two stages; one progressing V-shape and the other in the shape of a fan.

Fig. 22 is an enlargement of a strand break produced mechanically and submitted only to compare its fracture with those produced in line service. It may be mentioned that the reason the enlargements do not appear to be more circular is on account of the fact that the specimens had to be tilted slightly under the lens in order to use reflected light. A fact of some note is that, to date, the phenomenon described above has only occurred on the No. 1 size conductor, there being none to date on the No. 1/0 conductor.

Another reason which may be advanced for these failures is that the process of wire drawing in use at the time the cable was manufactured resulted in the wire being drawn too hard, and that the conductor vibrations set up by the wind causes any hard or brittle spots in the wire to crack. Once the crack is produced, it is only a question of time until under the possible combined influence of corona discharge and repeated flexure, the ultimate break will occur.

The abrupt rise of the mountains from the plains produce a change in temperature sufficient to keep air currents crossing the Boulder-Denver line almost con-

FIG. 23—PACK TRAIN USED ON CONSTRUCTION AND MAINTENANCE

tinuously. It has been observed that even slight air currents will set up and maintain vibrations which appear to have a greater amplitude at times than the segmental vibration caused by high winds. It is regretted that no specific data have been obtained on these lines which might enable some possible relation to be established among temperatures, length of span, stringing tension, frequency and amplitude of vibration.

To date no vibration troubles have been experienced on the aluminum conductors.

MAINTENANCE AND OPERATION

Maintenance methods have been developed which enable the patrol men to make repairs with the minimum of assistance. This has been made necessary by the inaccessibility of many parts of the line. Fig. 16 illustrates the working platform and "slack puller." The platform is suspended from the arms and guyed to the base of the tower. It provides a stable platform at a convenient height for work on dead-ends, and is

safe even in high winds. When necessary, hook ladders and planks temporarily attached to the towers are used for work on suspension strings.

The "slack puller" is a crank-operated tension device with sufficient gear reduction to enable one man to exert a tension of 10,000 pounds. Its use dispenses with heavy blocks and luff lines in insulation replacement work. This device was invented and patented by the Transmission Superintendent of this system.

In the mountainous regions where the line can be reached only over steep, rocky trails, burros are used in pack trains for transporting material. Fig. 23 shows this means of transportation.

Safety in Operation

There has been no fatal accident to any employee on the 100-kv. lines during the entire period of operation. One man was seriously injured in a fall from a temporary platform because he was not using his safety belt. There have been two accidents fatal to men not employed by the company. One occurred when a young soldier climbed a tower on a dare and fanned the conductor with his hat. The second accident killed a sheep herder and his horse when he rode into a line having insufficient clearance.

Grounded guard wires have been installed under the lines at important highway crossings, and the towers have been fenced or otherwise guarded in places which are particularly accessible.

Responsibility for safe operation of the lines rests largely with the dispatchers. Patrolmen keep the dispatcher informed of their movements, and when patrolmen do not report on schedule, additional help is sent out. This protection is particularly necessary in mountainous country where blizzards are not infrequent, and where falls or snow slides may disable men.

Safety and first-aid work is emphasized, and a wholehearted attempt is made to "sell" the idea of doing work safely, rather than to enforce rigid rules of safe conduct. Monthly meetings are held where safety and operation are discussed, and where any employee may voice pertinent ideas or opinions.

Linemen are divided into groups and if no time is lost on account of accidents to any member of the group in a three months' period, each member is given a pair of pliers, suit of overalls, pair of gloves, or similar useful article.

Conclusions

No exceptional difficulties have been encountered in high-altitude operation; jumpers at dead-end towers should be supported where wind velocities are high.

Insulation problems are no more serious than at sea level.

Arc points appear to be desirable at both ends of insulator strings. Copper and steel conductors operating above the critical voltage for corona for many years do not show unusual depreciation.

Horizontal configuration appears to be more desirable than vertical configuration, and properly built ground wires are probably effective.

Satisfactory relaying of high-voltage lines has been accomplished without great difficulty.

Discussion

Harold Michener: Some of the conductor failures were said to be due to wind, or thought to be due to wind. I should like to ask if it was thought that the wind forces caused those conductors to part without burning or whether it was the wind that blew the conductors into the tower or the two conductors together, after which they burned down.

M. T. Crawford: The Puget Sound Power & Light Company has operated a 120-mi., 110-kv. line across the Cascade range for about six years. Although the altitudes are not as great as those described in this paper, the ice and snow formation and weather conditions appear equal if not worse. The experiences on this line were described in a paper presented at the Pacific Coast Convention of the Institute in October, 1923.[1] Subsequent to the presentation of this paper, additional reconstruction work was done, following which there have been five years of very successful operation without a *single* interruption due to failure in the extreme loading section.

As finally reconstructed this line is built on standard steel towers with horizontal conductor arrangement, using 350,000 cir. mil 19-strand hard-drawn copper cable. No dead-ends are employed, all wires being held by suspension strings, each consisting of two standard strings yoked together in parallel, and free to swing at both tower and clamp. This method of construction permits free movement of conductors lengthwise of the line and eliminated the troubles which were first experienced from wires being jerked in two at dead-ends by the falling off of large sections of the snow and ice formation which builds up to 2 ft. in diameter.

All of the diagonal and horizontal angles were removed from the steel towers up to the snow line and in their place heavy angles were installed paralleling the corner leg members, eliminating the serious trouble which was at first encountered by the bending and shearing of angle braces by the settling of the heavy snow crust in the Spring.

Fortunately lightning is infrequent in the Puget Sound region. Only six interruptions have occurred in the five years from troubles of all kinds on this line, two of which were from lightning.

I should like to ask the authors of this paper if the troubles from broken conductors on the Shoshone-Denver line, noted in Table III, included any breakage of the character referred to above, due to the ice loading or to jerking action at times of dropping off of such loading.

H. H. Plumb: I should like to ask the authors if they have evidence of any unusual wind velocity at the high points across the passes. In my experience the evidence has been very plain that the wind velocity at the top of a fairly high mountain has been exceptionally high, of the order of a hundred miles per hour. That figure has been obtained by taking the size of the ice coating at the time when failures occurred, which was about 4 in. in diameter on a ⅜-in. diameter conductor of steel, and calculating the wind velocity that must have been present to break such conductors.

I should like to ask the authors if they have encountered any such high wind velocities as that.

G. B. McCabe: I wish to question the wisdom of leaving that word "probably" in the conclusions under the next to the last paragraph—"properly built ground wires are probably effective."

1. *Transmission Line Construction in Crossing Mountain Ranges*, M. T. Crawford, Trans. A. I. E. E., Vol. XLII, 1923, p. 970.

In the case of the Detroit Edison Company, we should leave the word "probably" out of such a statement.

We have a section of a double-circuit, 120,000-volt line between Trenton Channel and Marysville power houses, which runs through a particularly bad area in respect to lightning. During the 1925 lightning season on this double-circuit line in this particular section between Marysville and Superior Substations we had 44 lightning storms and 107 trip-outs. The following Winter we equipped the bad section with ground wire, a single ground wire of the same size as the conductors, *viz.*, No. 000 supported in the peak of the tower, and during the next or 1926 lightning season, with 34 electrical storms we had only seven trip-outs. We therefore feel that the use of ground wires is decidedly effective.

W. D. Hardaway: Mr. Michener asked if wind forces caused the actual failures. My impression is that they did not. I think that at the time the worst trouble was being experienced the line was equipped with ground wire at that point and the conductor was blown into the ground wire and burned, or at least nicked, and failed later.

Mr. Crawford's discussion was certainly an "eye-opener" to the operators in Colorado. Our snow loading and ice loading isn't as severe as that. We have large volume of frost formation but it isn't very heavy. Also, his service record of six outages in five years was certainly very interesting to us.

As to failures by jerking action of ice loading, I don't believe that has been experienced for the reason that the ice loading is not very dense. It is sometimes a foot in diameter but not heavy. Some of the failures which have occurred have been where the line was buried under snow and the snow suddenly settled and took the line out. It is rather interesting that some of those lines have operated actually under the snow, through tunnels in the snow.

Mr. Lloyd spoke of whipping of conductors on the Argentine Pass. The particular experience given in Mr. Thomas' paper was obtained on another line, Boulder Canyon, on a very steep hillside, and with a lighter conductor than the line across Argentine. However, there has been some wind trouble at Argentine which was helped by dropping the middle conductor and obtaining increased separation vertically.

The wind velocities which were mentioned are of interest to us. I can't speak with definite knowledge, but we have reports of 150-mi. wind velocities on Argentine Pass. Of course, those velocities should be corrected to sea level. They do not have as destructive action at 13,000-ft. altitude as they would have at sea level.

A-C. Elevator Motors of the Squirrel-Cage Type

BY E. E. DREESE[1]

Member, A. I. E. E.

Synopsis.—*This paper sets forth the features of squirrel-cage motor design which differentiate it from standard motors. Much of the paper is devoted to the two-speed motor with two separate stator windings having speed ratios of 2/1, 3/1, 4/1, and 6/1. The two-speed motor with a single winding is limited to the 2/1 ratio. Higher ratios are necessary for high elevator speed and low and accurate landing speed.*

The elevator motor is subjected to continual starting and stopping. The effects of inertia in such service are considered in connection with motor heating.

The proper division of slot area between the two stator windings and the problem of building a rotor with proper characteristics on both speeds are explained.

Noise elimination is necessary in elevator motors. The effect of this requirement in design is considered.

The effect of rotor skew is compared to the effect of distributed winding in the stator. The quantitative effect of skew is embodied in a constant called "skew factor."

The possibility of transformer effects between the windings of a two-speed motor is explained and methods of correcting to eliminate circulating currents are indicated.

* * * * *

THE induction motor as developed for elevator drive is a highly specialized type of machine. Slip-ring motors have been used, but the complications of control and the difficulty in eliminating noise have caused them to give way to the high-resistance squirrel-cage type. The high-resistance rotor gives a speed-torque characteristic which insures that the motor will have no points of mechanical instability and the motor will not pull-out and stall. The high-resistance rotor can be designed to give the maximum torque when starting and the torque per ampere is high. Another advantage of the high-resistance rotor is that it reduces the stator heating during a change of speed.

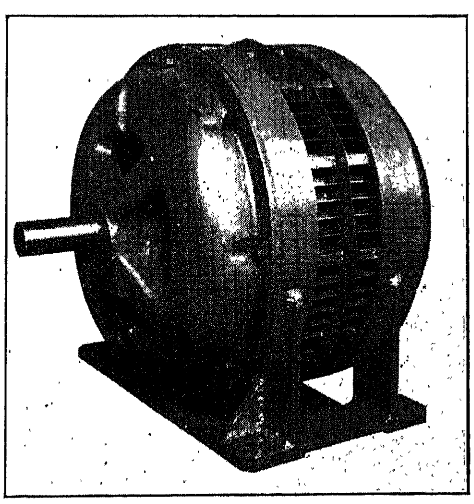


FIG. 1—SQUIRREL-CAGE TYPE ELEVATOR MOTOR

For a low-speed elevator the stator is usually wound for a single speed. For higher speeds the motor is built for two speeds since at high elevator speeds it is more difficult to make accurate landing. In the case of two-speed motors, the high-speed winding is generally used for starting and running and the low-speed for retarding and landing. The speed ratio required for the two windings should be greater the higher the speed of the elevator. Common speed ratios are 2-1, 3-1, 4-1, and 6-1. The high speed usually has four poles or more and the low speed 48 poles or less. A common motor for high-speed elevators has eight poles on the high speed and 48 poles on the low speed, running at synchronous speeds of 900 rev. per min. and 150 rev. per min. respectively on 60 cycles. The speed-torque and current-torque curves of two representative motors are shown in Figs. 2 and 3.

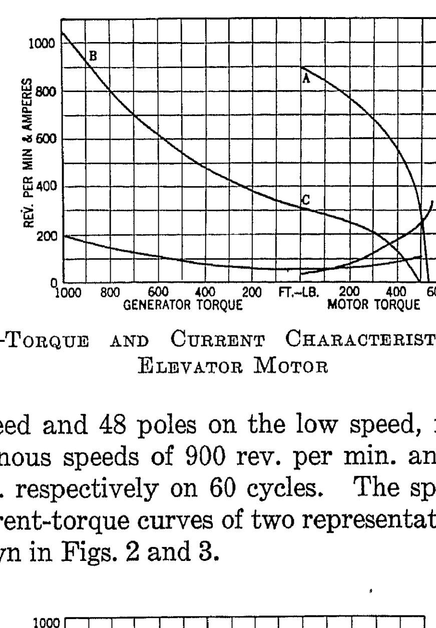


FIG. 2—TORQUE AND CURRENT CHARACTERISTICS OF 3-1 ELEVATOR MOTOR

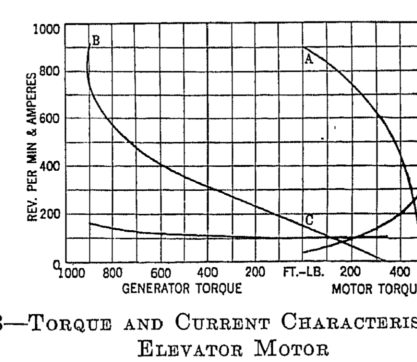


FIG. 3—TORQUE AND CURRENT CHARACTERISTICS OF 6-1 ELEVATOR MOTOR

Performance calculations on the high-speed winding are much simpler than on the low-speed winding. The conventional methods of calculation by the use of the circle diagram are possible only with the higher speeds. With the lowest speeds such as with 48 poles, the con-

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1. Chief Engineer, Lincoln Electric Co., Cleveland, Ohio.

Presented at Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

ventional circle diagram cannot be used. The reason is that the stator winding has high resistance and reactance characteristics due to the large number of turns of relatively small wire required. The idle current is practically the same as the starting current. There is a method of using a circle diagram for this type of motor in which diagrams the circle is displaced and tipped from its ordinary position. This method has been described by Behrend and makes use of McAllister's Transformations. But this graphical method has not been found convenient and expeditious for design work. Calculations using the constants of the circuits have proved much less laborious.

These motors are wound for star connection but the leads going to the neutral are brought out of the machine separately instead of being connected inside. This allows the user to insert resistance for starting, if desired, at the neutral point where the voltage between phases is low and the insulation problem in the control is thereby made simple. With this arrangement the wiring arrangement of the control is likewise simplified.

Inertia Loads

In order to understand the design problems in this motor, it is necessary to grasp the fundamental ideas of the type of load the motor is required to handle. Consider the simple mechanical arrangement consisting of a motor driving a drum over which is hung a cable carrying an elevator cage on one end and a counterweight on the other. The counterweight is usually enough to counterbalance the weight of the cage and a certain portion of the capacity load. This portion is usually in the neighborhood of 40 per cent. Thus, with a load of 40 per cent of capacity the weights on the two sides of the drum are equal and the motor has no load except to accelerate the masses and to overcome friction. It might seem that under this condition the motor hasn't much to do, but both theory and practise show that the condition with exact counterbalancing is little different from an unbalanced load in so far as the heating of the motor is concerned. Every time the machine is started the motor must transfer energy from the electric lines to the moving parts and then reabsorb this kinetic energy in connection with the brakes when the machine slows down to stop. During rush hours when stops are being made at nearly every floor this creation and destruction of kinetic energy becomes a dominating factor in the load and consequently in the design of the machine. The energy relations involved in the accelerating and retarding of an induction motor with a pure inertia load are easily derived.

The mechanical power output of the rotor is given by

$$\text{mechanical power output} = K\,\omega\,T$$

Where ω and T are the angular velocity and the torque respectively and K is a constant depending upon the system of units. From elementary induction-motor theory the electrical power input to the rotor is given by

$$\text{Electrical power input} = K\,\Omega\,T$$

Where Ω is the angular velocity at synchronous speed. Since the load is inertia only

$$T = \frac{I}{g}\,\frac{d\,\omega}{d\,t}$$

Where I is the *equivalent* moment of inertia of the rotor and is determined by transferring all of the kinetic energy of the moving parts of both motor and connected load to the rotor. The *energy* relations for the rotor during change of speed may then be set up as

$$\text{Mechanical energy output} = \frac{K\,I}{g}\int_{t_1}^{t_2}\omega\,\frac{d\,\omega}{d\,t}\,d\,t$$

$$= \frac{K\,I}{2\,g}\,(\omega_2^2 - \omega_1^2) \qquad (1)$$

$$\text{Electrical energy input} = \frac{K\,I\,\Omega}{g}\int_{t_1}^{t_2}\frac{d\,\omega}{d\,t}\,d\,t$$

$$= \frac{K\,I\,\Omega}{g}\,(\omega_2 - \omega_1) \qquad (2)$$

The expression (1) simply states that the mechanical output of the rotor during change of speed is equal to the change of kinetic energy. The above expressions are general. Their significance will become clear if certain special cases are considered.

Rotor Efficiency During Acceleration

If an induction motor comes up to synchronous speed from standstill

$$\omega_1 = 0 \qquad \omega_2 = \Omega$$

$$\text{In this case rotor output} = \frac{K\,I\,\Omega^2}{2\,g} \qquad (3)$$

$$\text{rotor input} = \frac{K\,I\,\Omega^2}{g} \qquad (4)$$

It is thus seen that

$$\text{Rotor loss} = \text{kinetic energy}$$

This relation is true whatever the rotor or stator resistance and whatever the flux density. Indeed all of these quantities may be variables during the process of acceleration.

Rotor Efficiency During Retardation

In elevator operation the process of retardation from high speed consists of throwing over to the low-speed winding. The low-speed winding is then running above synchronous speed and will act as a generator. It will transfer some of the kinetic energy of rotation back to the line. Reference to the curves in Figs. 2 and 3 will show the situation. With the high speed in operation the elevator with pure inertia load is operating at

point A. After the shift to low speed it is operating at B and the rotor is subjected to retarding torque. The rotor is retarded until it is in low-speed synchronism at C.

The energy relations for this process may be derived from expressions (1) and (2) in which is substituted the new synchronous speed Ω/Z. Also

$$\omega_2 = \Omega/Z \text{ and } \omega_1 = \Omega$$

Substituting in (1) and (2) there results

$$\text{rotor mechanical output} = \frac{K\,I}{2\,g}\left(\frac{\Omega^2}{Z^2} - \Omega^2\right)$$

$$= -\frac{K\,I}{2\,g}\,\Omega^2\left(\frac{Z^2-1}{Z^2}\right) \qquad (5)$$

$$\text{rotor electrical input} = \frac{K\,I}{g}\;\frac{\Omega}{Z}\left(\frac{\Omega}{Z} - \Omega\right)$$

$$= -\frac{K\,I}{g}\,\Omega^2\left(\frac{Z-1}{Z^2}\right) \qquad (6)$$

The negative signs show that the machine is now a generator with mechanical input, derived from the change in kinetic energy and electric output from the rotor to the stator.

If the rotor electrical output $\frac{K\,I}{g}\,\Omega^2\,\frac{Z-1}{Z^2}$ be divided by the high-speed kinetic energy from expression (3) there will result an expression showing the portion of the high-speed kinetic energy which is returned to the stator by regenerative braking. This expression is

$$\frac{\text{energy returned}}{\text{high-speed kinetic energy}} = 2\left(\frac{Z-1}{Z^2}\right) \qquad (7)$$

It is now possible to make up a table showing what becomes of the kinetic energy of the rotor and load when a shift is made to low speed and when after low-speed synchronism is reached mechanical brakes are applied. The unit of energy is the kinetic energy at high-speed synchronism.

TABLE I

Z (speed ratio)	2	3	4	6
Original kinetic energy	1	1	1	1
Portion returned to stator from (7)	0.5	0.44	0.37	0.28
Portion lost in mechanical brake	0.25	0.11	0.06	0.03
Portion lost in rotor winding	0.25	0.45	0.57	0.69
Rotor loss per cycle	1.25	1.45	1.57	1.69

The last line shows the units of energy going into rotor loss for one complete cycle consisting of starting on high speed, changing to low speed, and applying a brake. If the mechanical brakes be applied and the winding disconnected before low-speed synchronism is reached, they will absorb a disproportionate amount of energy and the portions returned to the stator and lost in the rotor will be reduced.

Stator Losses

So far, emphasis has been laid upon rotor loss and little has been said concerning stator losses. The reason for this is that with a high-resistance rotor most of the power loss is in the rotor. Once the rotor loss is known for inertia loads the stator loss is not difficult to determine since

$$\frac{\text{Stator loss}}{\text{Rotor loss}} = \frac{\text{stator resistance}}{\text{rotor resistance}}\,.$$

where the rotor resistance is the value after being transformed to the stator.

This relation holds true for any induction motor which has stator resistance and reactance low enough that the total currents in the rotor and stator are substantially equal and opposite. This condition is true for the high-speed winding and also for low-speed windings providing their speed is not too low. The above expression shows the advantage to the stator of the high-resistance rotor in the matter of stator loss on inertia load. The rotor loss is constant no matter what the rotor or stator resistance or the manner of applying voltage to the machine terminals. A high-resistance rotor reduces the stator loss. It is evident that the insertion of resistance in the stator leads for purposes of control has no effect upon the relation given above. The only effect is to spread the change in speed out over a greater time and to incur additional losses in the control resistance.

For those low-speed windings where stator resistances cause the performance to depart from classical circle-diagram performance (roughly below 300 rev. per min. at 60 cycles) energy loss in low-speed stator winding can be easily determined by multiplying the power loss of the stator when running idle by the time the low speed is in operation during each cycle. This is possible because the low-speed current does not vary much over the range of speed involved.

It is thus seen that with the exception noted above, the kinetic energy stored in the load is a measure of the heat developed in both the rotor and stator windings for inertia loads.

As an example of the importance of the load imposed by starting and stopping in comparison with running, consider the case of a certain motor. It is a 6-1 speed ratio and when the rotor is up to speed it alone has 15,200 ft.-lb. of kinetic energy. Couplings and brake drums revolving at the same speed will add possibly 4000 ft.-lb. The cage, with load, and counterweights may add 5000 ft.-lb. more. The total kinetic energy is then 24,200 ft.-lb. Since this is a 6-1 motor the energy transformed into heat in the rotor for a single start and stop will be

$$1.69 \times 24{,}200 = 40{,}500 \text{ ft.-lb.}$$

With capacity load the rotor has an output of 27 hp. and the slip is 16.6 per cent. With this capacity load the motor must run 13.5 sec. on high speed to have an energy loss in the rotor equal to the loss from starting and stopping. At 450 ft. per min. this would mean seven floors of high-speed running; this would mean

nine floors between stops. When it is considered that with heavy loads frequent stopping is necessary it is evident that the starting and stopping develop most of the heat in the machine. Since the kinetic energy is a measure of the heat loss in the elevator motor, it is advantageous to keep the kinetic energy as low as possible in order to keep the motor temperature down. Most of the kinetic energy is stored in the rotor of the motor and those parts of the elevator machine which are directly connected to the motor shaft. The energy storage in the more slowly moving parts and in the elevator cage and counterweight are seldom, if ever, greater than 20 per cent of the total, so the rotor and next adjacent parts store about 80 per cent of the kinetic energy.

Quite obviously, then, the rotor and associated parts should have the smallest moment of inertia possible consistent with good design. The rotor lamination should be stacked on a spider to eliminate the weight of lamination that would otherwise run to the shaft. The spider itself can be designed to make a not inconsiderable saving in weight. Welded steel spiders which, in one case, weigh 43 lb. apiece displaced cast iron spiders which weighed 89 lb. apiece. The magnetic circuit and electrical circuits of the rotor should be worked at higher densities of flux and current than is permissible in continuous duty industrial motors in order to keep the mass of the rotor down to low values. In this connection, the elevator builder has his part to do in keeping down inertia losses. He should reduce as much as possible the weight of all moving parts particularly those working at the higher speeds.

The problem of dissipating the heat evolved in the motor is accentuated by the fact that the ventilation is materially cut down owing to the accelerating and retarding features of the service which keep the average speed of the motor at less than one-half of the high speed. It is necessary, therefore, to provide special means for transferring the heat developed to the ventilating air. To this end the areas of all air passages through the machine should be four or five times greater than for standard motors. This has been made possible to large extent by using arc welded steel instead of cast iron for frames. Extra large blower paddles are provided on the rotor to increase the volume of air moved as well as to conduct the heat from the rotor to the air stream. Since most of the heat in the machine is developed in the high-resistance rotor it is important to abstract as much as possible from the rotor without requiring it to cross the air-gap and heat the stator. The stator is provided with ventilating fins which are in the path of the air issuing from the motor. The circumferential fin is set into the stator lamination and draws heat from deep in the laminations. The cross fins span all the laminations and are arc welded in place. See Fig. 1.

The problem of heat dissipation increases rapidly with increase in diameter of the rotor. If we consider comparative designs at the same speed and lamination length we find for the ordinary motor that to a first approximation the various constants vary with the diameter D as listed.

Torque	Running loss	Moment of inertia	Starting and stopping loss
D^2	D^2	D^4	D^4

The reason that the moment of inertia varies as the fourth power of the diameter is that the radial depth of the rotor lamination must vary as the diameter. This condition shows that as the diameters of elevator motors are increased in order to get more torque the heating problem due to inertia load gets rapidly more acute—and means for cooling the machine will become a constantly increasing problem.

These motors bear a horsepower rating but this rating is an empirical expression only. The horsepower is generally calculated by assuming the motor to be running at 90 per cent of synchronous speed and developing 40 per cent of the starting torque. A more useful rating is the starting torque in foot-pounds as a torque calculation is more simple and direct than a power calculation. The starting torques available in standard motors range from 10 to 2800 ft.-lb. with empirical horsepower ratings ranging from 1 to 150 hp.

Noise Elimination

Noise elimination is of paramount importance in elevator motors. The magnetic hum so characteristic of ordinary induction motors becomes an insidious nuisance in a location where people must live with it. Hotels, apartments, offices, and hospitals demand noiseless operation. The predominant cause of noise in induction motors is the existence of harmonics of both flux and current. Elementary induction motor theory assumes that there is a single sinusoidal field rotating at synchronous speed. It is, however, well known that if the actual distributions of conductors and currents are analyzed according to Fourier's method the field is really composed of a multitude of harmonic fields rotating some forward and some backward. These fields are fairly well damped out by the rotor bars but the damping process requires harmonic currents in the rotor. The interaction of these currents and fields sets up periodic forces which in turn move the rods and teeth enough to produce noise. Pitch or coil span is known to have a vital connection with the production of harmonics and since the 5th and 7th tend to have the greatest magnitudes it is well to keep them as low as possible. This can be done by making the pitch or span equal to approximately 5/6 of a pole pitch. The number of slots per phase per pole is closely connected with the production of harmonics. Here again Fourier's analysis shows considerable improvement in this regard of a motor having two slots per phase per pole over one having a single slot per

phase per pole. For this reason one should set two slots per phase per pole as the absolute minimum if one is to have a quiet motor. It is common in general motor practise to use fractional number of slots per phase per pole. This is inadmissible in an elevator motor because the resulting dissymetry produces noise from the harmonics set up.

The requirement of a minimum of 2 slots per pole per phase results in stators with a greater number of slots than is common for the ordinary induction motor of equivalent size. If we consider a 900-150 rev. per min. motor for three-phase and 60 cycles we see that the low speed has 48 poles. This means that the stator has 288 slots where the standard motor of the same size and of course of higher speed, has only 96 slots.

Another persistent source of noise is in slot combinations as between rotor and stator. Every designer of induction motors has had noise troubles from this source which were corrected by changing the number of rotor bars. In this connection it was formerly the custom to select the number of rotor bars by some empirical rule but of late this method has been partially displaced by a more rational and analytical process—having to do with the harmonics set up by the rotor bars. In spite of this advance into less empirical methods this field is by no means conquered and it offers a fertile field for further investigation and report.

Rotor Skew

An interesting problem arose in connection with the skewing of the rotor rods. It is common practise among all manufacturers to skew rotors. This has two effects which it is desired to utilize. The first and most important is that with a properly skewed rotor there are no positions of the rotor where it tends to remain locked in position due to the variation in magnetic reluctance of the air-gap as the rotor is turned. This effect, sometimes known as "cogging", produces pulsations in torque if allowed to become of too great magnitude by improper amount of skew. A second effect desired from rotor skew is to reduce noise resulting from the pulsating torque. Then a third effect forced itself into the problem of design.

It happened that sometimes motors supposed to be identical in every respect showed variations in starting torque much too large to be accounted for by the ordinary variations usually encountered in building induction motors. This occurred for the most part on 48-pole windings. It was found to be due to the variations in skew of the rotor rods. As an example consider a 48-pole stator and a rotor with 90 skewed bars. The design would probably call for a skew of one rotor slot pitch. This skew is

$$\frac{48 \times 180 \text{ deg.}}{90} = 96 \text{ deg. (electrical)}$$

The effect is the same as that due to the distribution of a phase group in the stator over a plurality of slots except here the distribution is *continuous* instead of discontinuous as in the stator. To carry the comparison further consider the voltages generated in the stator and skewed rotor by a sinusoidal rotating magnetic field. In the stator if there are two slots per phase per pole each phase voltage generated in the stator consists of two components separated by an angle which is 30 deg. for three-phase and 45 deg. for two-phase. (See Fig. 4.)

$$\text{The distribution factor} = \frac{E_2}{2\,E_1}$$

The distribution factor may be defined as the actual voltage generated divided by the voltage that would be generated if the winding were concentrated.

In the case of skewed rotor rods it will be seen that each elementary length of rotor rod has an infinitesimal voltage generated in it which is out of phase with that

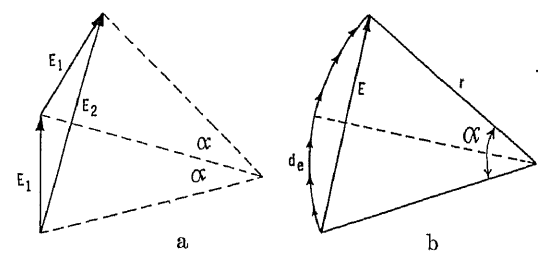

Fig. 4—Voltages in Stator and Skewed Rotor

a. Stator voltages, showing effect of distributing the winding in two slots per phase per pole. E_1 = voltage in ½ of 1 phase. E_2 = phase voltage. This effect is similar to the effect got in the squirrel-cage rotor by skewing the rotor bars.

b. Rotor voltages. With a skewed rotor bar the elemental lengths of the bars have infinitesimal voltages generated in them which are *out of phase* just the same as the voltages induced in adjacent slots of the stator are out of phase. The elemental vector voltages plotted end-on-end lie along the arc of a circle. The sum is the chord.

$$\text{"Skew factor"} = \frac{E}{\int_{\alpha=0}^{\alpha=\alpha} d\,e} = \frac{2\,r\,\sin\frac{\alpha}{2}}{r\,\alpha} = \frac{2\,\sin\frac{\alpha}{2}}{\alpha}$$

generated in the next adjoining element. The voltage generated in the rod is the integrated voltage of these elementary lengths. Vectorially we have the elementary voltages forming the arc of a circle and the sum is the chord. Hence, the voltage actually generated in a rotor rod is less than would be generated if the rod were without skew.

$$\text{The ratio } \frac{\text{actual voltage generated per rod}}{\text{voltage for unskewed rod}} \text{ might be}$$

called "skew factor."

It will be obvious that this ratio is independent of the slip and the result is that the torque is

$$\text{Torque with skew} = S^2 \times \text{torque without skew}$$

since the torque is measured by the rotor input and the rotor input varies as the square of the rotor voltage at any particular slip. An alternative way of satisfying oneself of the square relation expressed above is to

consider that since the voltage induced in a skewed rod is S times the voltage for an unskewed rod the current for skewed and unskewed rods will be in the same ratio. Now the current flowing in a skewed rod placed in an unskewed magnetic field will have elemental torques out of phase in the same manner that the voltages were out of phase. Fig. 4 can be used to illustrate the integration of elementary torques. Hence, the factor S enters a second time.

In Fig. 5 the skew factor S is plotted against skew in electrical degrees. The square of S is also plotted. When we refer to the latter curve we can see the importance not only of using this skew factor in our calculations, but also the importance of keeping variations of skew in practical manufacture down to certain narrow limits. As an example, suppose a rotor has 90 rods and is 20 in. in diameter. If it is operating in a 48-pole field with a skew of exactly one slot pitch we find the 100 per cent skew to be 0.70 in., the skew angle is 96 electrical degrees, and S^2 is 0.785. This means that the motor will deliver only 78.5 per cent of the torque

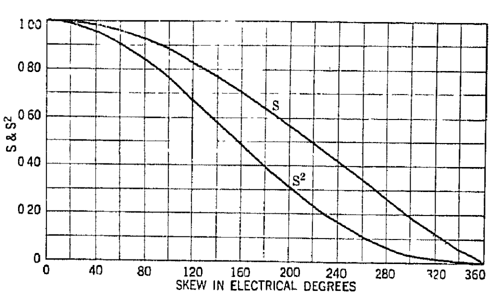

Fig. 5—Skew Factor Plotted Against Skew

"Skew factor" $S = \dfrac{360 \text{ Sin } \frac{\alpha}{2}}{\pi \alpha}$ where α is skew in electrical degrees

it would deliver if it were designed without skew. The effect of inaccurate skew can be shown in tabular form where "per cent skew" means the percentage of 1 slot skew.

Per cent skew	Inches skew	Skew angle	S^2
80 per cent	0.56	77 deg.	0.82
100 per cent	0.70	96 deg.	0.785
120 per cent	0.84	115 deg.	0.71

Thus, we see if the skew is held only approximately that the torque of the machine may vary by

$$\frac{0.82 - 0.71}{0.785} = 14 \text{ per cent}$$

This variation is too large to be neglected.

Stator Copper Balance

In the case of a two-speed motor with two separate windings the question of the proper balance of copper section between the two windings is of utmost importance. If this is not carefully attended to it will be found that out on the job one winding will be running hot while the other is cool. It is obvious that the proper division of slot area between the two windings depends upon the duty cycle of the elevator and the relative service demanded from the two windings. A little calculation of the losses in the two windings will show that the minimum amount of heat will be evolved in the stator windings when the ratio of the copper cross-sections of the two windings is equal to the ratio of energy (not power) losses in the two windings. That is,

$$\frac{A_1}{A_2} = \frac{Q_1}{Q_2}$$

Where A and Q represent the cross-sectional area of copper in the slot and the energy losses respectively and the subscripts identify the winding with which the particular quantity is associated.

While there are two stator windings there is only one rotor winding and it is necessary to build this rotor winding so that it will have the correct resistance for both speeds. The losses in the rotor winding occur in two parts of the circuit—in the bars and in the end rings. The ratio of these losses is given by the expression

$$\frac{\text{Ring loss}}{\text{Bar loss}} = \left(\frac{0.635\,N}{P^2}\right) \times \left(\frac{D}{L}\right) \times \left(\frac{A_B}{A_R}\right) \times (K)$$

Where P Number of poles
N Number of rotor bars
L Length of rotor bar
D Mean diameter of end ring
A_R Cross-sectional area of the end ring
A_B Cross-sectional area of one bar
K Ratio of conductivities of material in bar and material in ring (Unity for bar and ring of same material)

This expression shows that in a two-speed motor with a speed ratio of 6−1 the proportion of ring loss to bar loss on the low speed is 1/36 of its value on the high speed.

In one such rotor the ratio of ring loss to bar loss is 0.292 for the high-speed condition. On the low speed this ratio falls to 0.008. In this case the ring loss is negligible on low speed. It is then obvious in this case that the proper method of getting the desired rotor resistance on both speeds is to design the rods for low-speed operation and design the rings to go with these rods for proper high-speed design.

Transformer Effects in Two-Speed Stators

The design of the stator winding in a two-speed two-winding motor is subjected to limitations which are not present in a single winding motor because of the transformer effects between the windings. When one winding is in operation the revolving flux cuts the conductors of the other winding and sets up voltages in them. Great care must be taken that these induced trans-

former voltages do not set up parasitic currents in the idle winding and give trouble due to overheating and noise. In certain speed combinations, even though internal parasitic currents are eliminated, voltages appear at the terminals of the idle winding which may cause trouble with connected control apparatus.

When one winding is operating it is obvious that every conductor in the idle winding has the same e. m. f. induced in it as is induced in a conductor of the operating winding. The problem is to so connect each winding that these e. m. fs. either cancel each other out or at least do not set up parasitic currents when the windings are out of use and at the same time to so connect them that the operation will be proper when in use.

A full account of the analysis necessary to cover the subject of elimination of harmful transformer effects is long enough to form a paper in itself so the present paper will limit itself to brief explanations of methods, followed by tabulated results which would be obtained by extensions of the methods.

Elimination of Circulating Currents in the High-Speed Winding

We will first concern ourselves with transformer effects in the high-speed winding induced by operating the low-speed winding.

Correction by High-Speed Coil Pitch. If the speed ratio is, for instance, 2 it is evident that if the high-speed coils are wound full pitch the two conductors forming a turn will have e. m. fs. induced in them 360 deg. apart and the turn e. m. f. will be zero. If the speed ratio is 3 the turn e. m. f. will be zero if the high-speed pitch is 2/3 or 4/3. We may generalize and say if the speed ratio is Z the e. m. f. per turn of the high speed will be zero if the

$$\text{high-speed pitch} = \frac{2}{Z}, \frac{4}{Z}, \frac{6}{Z} \text{ etc., where } Z \text{ is}$$

always taken > 1 and may be fractional or integral. By using this pitch, the high-speed winding may then be connected any way desired without further thought to transformer effects in it. The designer, however, may not wish to use the coil pitch demanded by this type of correction because it may be a pitch conducive to noise from harmonics or it may be a pitch not physically attainable with the number of slots at his disposal. He must then accept turn voltages other than zero and expect to annul them in coil or group connections.

Correction in the Phase Group. In case the induced voltage per turn is not zero, the voltage per coil will be the turn voltage multiplied by the number of turns. The coils which make up a phase group are equally distributed over 60 electrical deg. in an ordinary three-phase winding. When the low speed is operating this 60 deg. is changed to $60 \times Z$ deg. This condition can be very simply shown by vectors in Fig. 6. The vectors A, B, and C represent the voltages induced in adjacent high-speed coils of the same phase group when the high speed is operating. These coils are always connected in series so that the group voltage is the vectorial sum. When the low speed is operating the span that was 60 deg. now becomes 60 deg. $\times$ Z because the electrical degrees between adjacent coils is Z times what it was before. This vectorial condition is shown in Fig. 7.

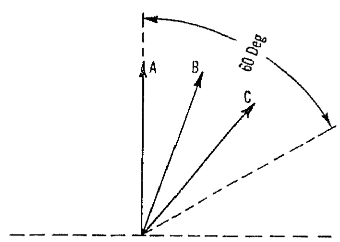

FIG. 6—VOLTAGES INDUCED IN HIGH-SPEED WINDING WHEN HIGH-SPEED WINDING IS OPERATING

In a three-phase high-speed winding the voltages A, B, C generated in the various slots of a phase group are spread over 60 electrical degrees *only* when the high speed is in operation. When the low speed is operating these vector voltages are spread over $60 \times Z$ deg.

It is obvious that for certain values of Z the vectors in a phase group will be equally distributed over 360 deg. In the three-phase case this condition occurs when $Z = 6$, a common speed ratio for elevator motors. In this case the coil voltages in a group add up to zero and the groups may be connected in any desired manner without reference to transformer effects. By extension of this reasoning we may summarize on corrections in the phase group.

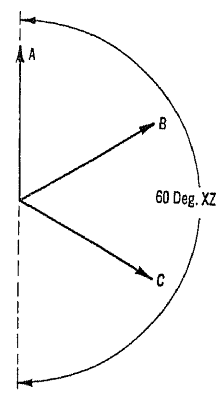

FIG. 7—VOLTAGES INDUCED IN HIGH-SPEED WINDING WHEN LOW-SPEED WINDING IS OPERATING

The vector voltages generated in a high-speed group are spread over $60 \times Z$ electrical degrees when the low speed is operating. The transformer voltage in a high-speed group is then $A + B + C$. In case 60 deg. $\times Z$ is a multiple of 360 deg., $A + B + C = O$.

Group voltages on the high speed will be zero for

3 phase (60 deg. distribution) when $Z = 6$, 12, or any multiple of 6

3 phase (120 deg. distribution) when $Z = 3$, 6, or any multiple of 3

2 phase when $Z = 2$, 4, or any multiple of 2

Correction by Group Connections. There occur many cases in two speed-windings where neither the turn

voltage nor the group voltage can be made zero, the latter for those speed ratios which do not occur in the above table. In those cases where one has a group transformer voltage in the high-speed winding with low-speed operating one must be careful that any internal parallel connections are not the seat of parasitic circulating currents due to these group voltages. Suppose one has a three-phase motor with four poles

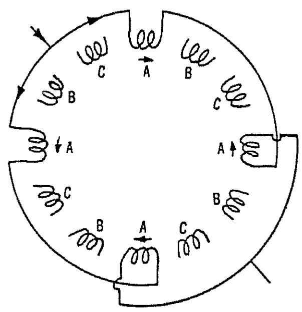

FIG. 8—STATOR CONNECTED SERIES-PARALLEL WITH ADJACENT POLES IN SERIES

Note that adjacent poles are reversed

on the high speed and 16 on the low speed in which the turn voltage has not been made zero by correction in coil pitch. There will then be transformer voltages in the 12-phase groups. Suppose the designer wishes to connect the four groups of a phase two series two parallel. There are two common ways of making this connection in single-speed motors—one is to connect the corresponding groups from adjacent poles in series and then parallel two such series of adjacent poles as in Fig. 8. The other method is to connect alternate poles in series and parallel the series of alternate poles as in Fig. 9. It is to be noted that in the adjacent connection the even numbered poles are reversed in the series while in the alternate connection there is no reversal inside the series. While either of these series-parallel connections would be permissible in a single-speed winding, it will be seen that one is limited to the adjacent connection when considering the transformer effect from a 16-pole field. Fig. 10 shows the arrangement of the four group voltages belonging to one phase when the high speed is operating while Fig. 11 shows the new array of vectors when the low-speed flux acts upon the high-speed winding. The angular distance between adjacent vectors has been increased from 180 deg. to 4 $\times$ 180 deg. because 4 is the speed ratio.

The adjacent connection gives $1-2$ in series in one leg of the parallel connection with $3-4$ in the other. Here we see that $1-2$ has zero transformer voltage as has also $3-4$. There will then be no trouble with circulating currents between the two legs of the parallel connection. On the other hand, the alternate connection shows $1 + 3$ paralleled with $- 2 - 4$. The vector arrangement with transformer voltages is shown in Fig. 12. This connection causes all the transformer voltages to add up in phase around the local parallel circuit and the circulating current will make the connection impossible.

Extending this analysis a table is now given which shows the number of poles which must be in series to make transformer voltage zero in a series leg and thus eliminate circulating currents in the high-speed winding with the low-speed operating.

TABLE II

Z	Adjacent connection	Alternate connection	
2, 4, 6, etc.	2	Impossible	Number of poles in series must be a multiple of number shown to eliminate transformer voltages in series leg of parallel connection.
3/2, 5/2, 7/2 etc.	4	2	
4/3, 8/3, 10/3 etc.	6	3	
5/3, 7/3, 11/3 etc.	3	3	
5/4, 7/4, 9/4 etc.	8	4	
6/5, 8/5, 12/5 etc.	10	5	
7/5, 9/5, 11/5 etc.	5	5	

It will be noted that the foregoing tabulation does not contain any speed ratios where Z is an odd number. The reason for this is that if the speed ratio is an odd number, it is impossible to connect the series circuits so that the voltage in a series leg is zero. It will be found, however, that with odd speed ratios the coils in the high-speed winding may be connected in any standard manner because it will always occur that the transformer voltage in one leg of a parallel connection is equal to the transformer voltage in the other leg (or legs) of that same phase and thus no circulating current will flow. (See Fig. 13.) This does mean, however, that there is a transformer voltage generated in each phase which voltage appears at the terminals of the machine. This fact may have a vital bearing on the type of control used with the motor.

ELIMINATION OF CIRCULATING CURRENTS IN LOW-SPEED WINDING

A little thought will show that it is impossible to

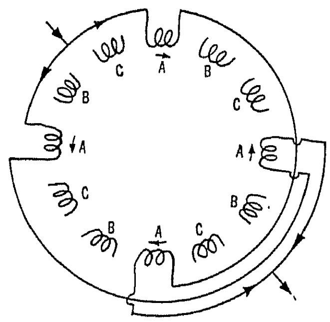

FIG. 9—STATOR CONNECTED SERIES-PARALLEL WITH ALTERNATE POLES IN SERIES

annul the transformer voltage in the low-speed winding by the first two devices used in the high-speed winding, that is, by choosing a particular coil pitch or by having the voltages in a group add to zero. The only recourse in eliminating trouble in the low-speed winding is to make sure that circulating currents cannot occur in any parallels by so connecting the proper poles in series that

the transformer voltage of a series leg is made zero just as was done in the high-speed winding. The following table will show the proper number of poles to be connected in series to obtain zero leg voltage for the various speed ratios and the two commonest type of connection, that is, adjacent poles in series and alternate poles in series.

TABLE III

Z	Adjacent connection	Alternate connection	
2	4	2	Number of poles in series must be a multiple of number shown to eliminate transformer voltages in series leg of parallel connection.
3	3	3	
3/2	6	3	
4, 4/3	8	4	
5, 5/3	5	5	
5/2, 5/4	10	5	
6, 6/5	12	6	
7, 7/3, 7/5	7	7	
7/2, 7/4, 7/6	14	7	

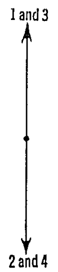

Fig. 10

Fig. 11

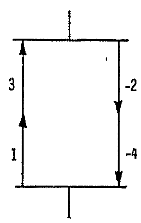

Fig. 12

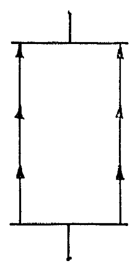
Fig. 13

Fig. 10—Group Voltages in High-Speed Winding When High-Speed Winding is Operating

These are the four group voltage in one-phase of a four-pole stator. The distance between successive voltages is 180 electrical degrees.

Fig. 11—Group Voltages in High-Speed Winding When Low-Speed Winding is Operating

When the high-speed winding of Fig. 10 is subjected to the low-speed field of 16 poles the successive polar voltages are 4 $\times$ 180 deg. apart because 4 is the speed ratio

Fig. 12—Local Circulating Currents Set Up in High-Speed Winding With Series-Parallel Connection

These currents are induced by transformer effects from the low-speed winding

Fig. 13—Transformer Voltages Set Up in High-Speed Winding When the Speed Ratio is an Odd Integer

No circulating currents can occur but induced transformer voltages do appear at the terminals of the high-speed winding

As an example of the use of these tables, suppose it is wished to build a 3-phase motor with synchronous speeds of 900 and 225 rev. per min. This is a 4 − 1 ratio. There will be 8 and 32 poles. If there are 192 slots there will be 24 slots per pole on the high speed and 6 on the low speed.

Transformer voltage in the high speed may be eliminated at the start by making the pitch $P = Z/4$ which in this case is $P = 1$ since $Z = 4$. But, it may not be desired to wind this high speed with full pitch due to harmonics or due to the fact that the designer desires a shorter pitch to obtain the proper flux density. He will then have transformer voltages in the coils. He will also have transformer voltages in the groups and the question remains how to connect the groups to obtain zero leg voltage. Table II shows that if he connects adjacent poles in series only two poles to a series leg are needed although any multiple of two may be used. He may then connect the high-speed groups

2 series	4 parallel
4 series	2 parallel
8 series	

He also sees that no parallel connection is possible if he connects alternate groups in series.

Turning now to the low-speed winding, he sees the limitations from Table III. This table tells that circulating currents in parallels will be eliminated if he has multiples of eight poles in series with the adjacent connection and multiples of four poles in series with the alternate connection. We may then connect the 32 poles as follows:

Adjacent Connection		Alternate Connection	
8 series	4 parallel	4 series	8 parallel
16 series	2 parallel	8 series	4 parallel
32 series		16 series	2 parallel
		32 series	

Conclusion

The growing demand for and use of a-c. elevators is natural since d-c. is more expensive to produce and distribute than a-c. In case a-c. only is available in a given locality it is necessary to install conversion apparatus in addition to the elevators in order to operate d-c. elevators. There is every indication that the use of a-c. elevators is in its infancy. As the use is extended the design problems and their solutions which are the subject of this paper will represent, it is hoped, a substantial start in the more economical use of electric power and invested capital in this particular field.

Electric Welding of Pipe Lines

BY J. D. WRIGHT[1]
Associate, A. I. E. E.

Synopsis.—This paper outlines the process of manufacture of steel pipe from flat rolled steel plates by automatic metallic arc welding. Data are given showing the physical and chemical analysis of the plate, the weld, and the welding wire, as well as the speed of welding and electrode and power consumption.

* * * * *

THE economies which have been effected in many manufacturing operations during the past few years by the adoption of electric arc welding for manufacturing as well as for tool repair have been so outstanding as to command the attention of all industries.

In many cases, the reduction in cost has been accompanied by a distinct improvement in quality, so that in these days of increasingly keen competition, no manufacturer marketing a product in which fabricated metal parts are, or might be used, should fail to make a thorough study of the possibilities of electric welding.

One of the newer applications of automatic arc welding is in the fabrication of pipe from flat rolled steel plates. It is particularly applicable to the larger sizes of steel pipe which heretofore have been made either by riveting, by the lock-bar process, or by the hammer weld process. The interest aroused by several successful installations of lines of pipe fabricated by the electric arc welding process has been very widespread, and it is the purpose of this paper to discuss the present state of the art as exemplified by a recent installation.

The example selected is the process employed for fabricating the pipe for a line approximately eight miles long, to convey water from the Provin Mountain Reservoir to the City of Springfield, Massachusetts. From the reservoir to the west bank of the Connecticut River, a single line of 54-in. and 48-in. diameter pipe is used. Two lines of 36-in. diameter each are laid under the Connecticut River, and from its east bank a single line of 48-in. and 42-in. pipe connects with the present distribution system of the City of Springfield. The thickness of the plate used in the pipe varies from 5/16 to 1/2 in.

Tests of Welded Joints

Before bids on welded pipe were submitted, tests were made to determine the strength of the welded joint and a definite procedure was worked out to insure thoroughly reliable and uniform results.

The plates used for the tests were of fire-box steel with tensile strength between the limits of 52,000 and 62,000 lb. per sq. in., as specified by the Engineer of the Board of Water Commissioners. The following shows typical analysis and physical properties of the plate steel:

Carbon......	0.20 per cent	Yield point—	35,450 lb. per sq. in.
Manganese...	0.40	Tensile strength	57,500 lb. per sq. in.
Phosphorus ..	0.015	Per cent elongation	31.5
Sulphur	0.029	Per cent reduction of area	56.3

Sections 3 in. wide by 48 in. long were sheared from ½-in. plate, and the sections beveled on one 48-in. side as shown by Fig. 1. Two sections were then welded together using the multiple arc process. This will be described in greater detail later. Two beads were deposited, the first with 3/16 in. G. E. type "F" welding electrode using 300/320 amperes at an arc voltage of 18/22, and the second with 3/16 in. G. E. type "B" electrode using 320/360 amperes and 18/22 volts. The welding was done at a speed of approximately 4½ in. per minute.

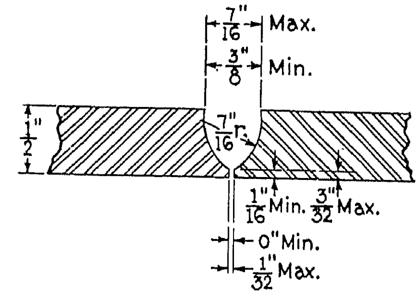

FIG. 1—DIMENSIONS OF BEVEL FOR WELDING ½-IN. PLATES

The following table shows chemical analysis of the two welding electrodes:

	G. E. type "B"	G. E. type "F"
Carbon......................	0.10 max.	0.13/0.18
Manganese..................	0.25/0.45	0.40/0.60
Sulphur......................	0.045 max.	0.03 max.
Phosphorus..................	0.03 max.	0.45 max.
Silicon......................	Trace	Trace

Type "F" is a solid wire to which a special treatment is given to insure a uniform flowing quality. Type "B" has a center metallic core surrounded by a layer of flux, the whole being incased in a metallic sheath.

The welded plates were cut into strips 1½ in. wide and tested for tensile strength in a standard testing machine. The following results are typical of many specimens:

1. Industrial Engineering Dept., General Electric Company, Schenectady, N. Y.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

Specimen	Tensile strength lb. per sq. in.	Failure
1	56,700	Weld
2	61,700	Weld
3	60,200	Steel
4	61,870	Steel
5	55,700	Weld
6	60,600	Steel

Other specimens were subjected to various bend tests to check the ductility of the weld.

Fig. 2 shows very clearly the metal deposited by the first and second arcs and the zone in the plate stock into

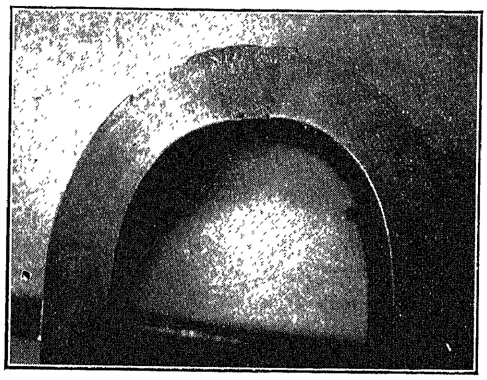

FIG. 2—DEEPLY ETCHED SECTION OF MULTIPLE ARC WELDED ½-IN. PLATE

which the heat of the weld has penetrated. Photomicrographic studies of the grain structure of the steel in the weld and adjoining plate show total lack of a

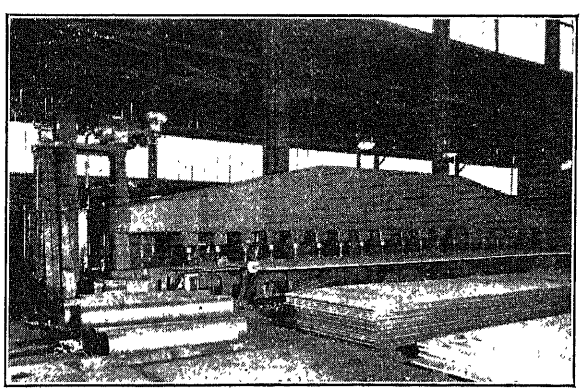

FIG. 3—36-FT. PLATE PLANER WITH TWO PLATES IN POSITION FOR MACHINING BEVEL ON 30-FT. SIDE

definite line marking the transition from the weld to the plate, and no evidence whatever of any injury to the plate, owing to heat of the weld.

MANUFACTURE OF PIPE

The pipe for the Springfield water line is made in 30-ft. lengths from two 30-ft. plates which are bent into half circles and automatically arc welded together. Some consideration was given to welding of the circumferential joints in the field, but because of considerable opposition, it was decided not to do this on this particular job, and the 30-ft. sections are riveted together. To provide for this the plates are sheared so that the pipe diameter increases slightly from one end to the other, thereby permitting the small end of one section to fit into the large end of the next section an amount required for the riveted joint.

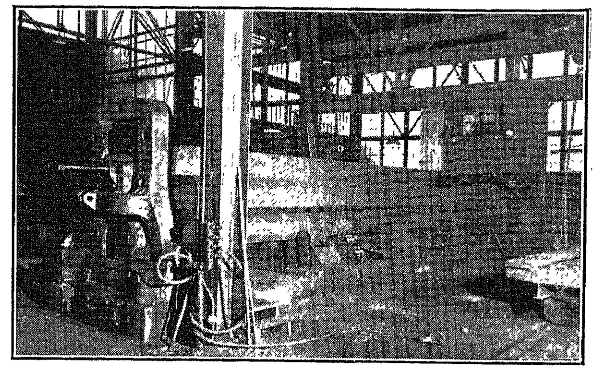

FIG. 4—36-FT. BENDING ROLLS FORMING 30-FT. HALF SECTION OF 48-IN. PIPE

The first operation in the manufacture of the pipe after the flat plates have been sheared to size is to bevel the sides accurately as shown in Fig. 1. This is done simultaneously on two plates on the plate planer shown in Fig. 3. On each plate, two lines are then scribed, each parallel to the upper edge of the bevel and ¾ in. from it.

The plate is then taken to the bending rolls, (Fig. 4), and by means of a special jig, the two 30-ft. edges are bent to the proper radius. The whole plate is then formed into a true half circle. Next the two halves of the pipe are placed in a specially designed frame, (Fig. 5), and tack welded together approximately every

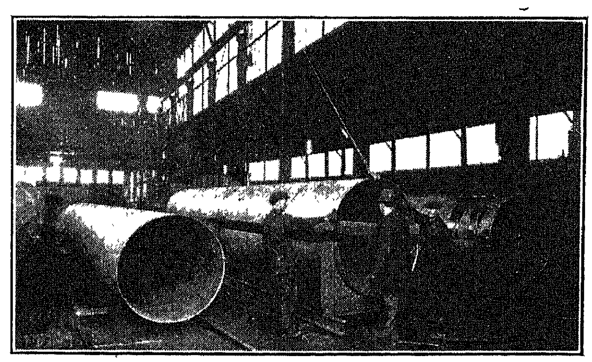

FIG. 5—FRAMES OF SPECIAL DESIGN SUPPORT THE TWO 30-FT. HALF SECTIONS OF 48-IN. PIPE WHEN BEING TACK WELDED BY HAND FROM THE INSIDE

16 in. on the inside by hand. After the raised portions of the beads are removed by grinding, the pipe is placed in the automatic welding machine, (Fig. 6).

PIPE WELDING MACHINE

The pipe welding machine consists essentially of three horizontal beams, two above and one below.

Enclosed in the lower beam and extending throughout its full length are several sections of fire hose to which compressed air can be admitted. On the hose rests a series of plungers which in turn supports a "backing-bar," the latter being fitted with a flat copper chill bar approximately two inches wide. Application of compressed air causes the hose to expand, thereby raising the plungers, and the copper strip in the backing-bar is

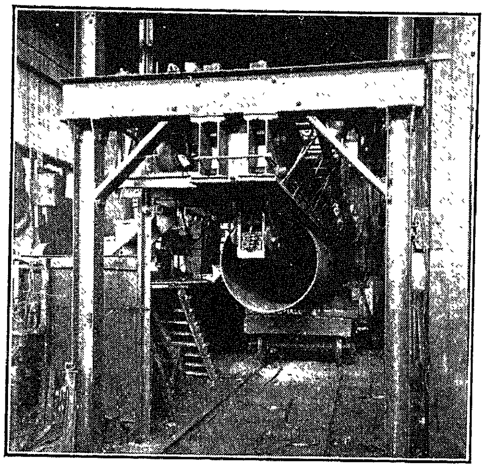

FIG. 6—END VIEW OF 36-FT. PIPE WELDING MACHINE SHOWING 30-FT. SECTION OF 48-IN. PIPE READY FOR AUTOMATIC ARC WELDING OF LONGITUDINAL SEAM

pushed up against the under side of the joint at a pressure of 200 lb. or more per running inch. The backing-bar is also provided with an insulated conductor which forms part of the return circuit for the welding current. By shunting the proper amount of current through this bar when the pipe is being welded, the

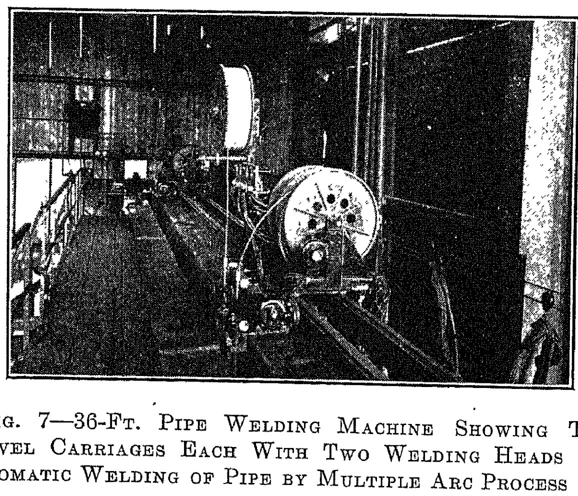

FIG. 7—36-FT. PIPE WELDING MACHINE SHOWING TWO TRAVEL CARRIAGES EACH WITH TWO WELDING HEADS FOR AUTOMATIC WELDING OF PIPE BY MULTIPLE ARC PROCESS

magnetic disturbances of the arc can be very effectively controlled.

To the lower side of the upper beams of the machine are attached two copper jaws spaced approximately two inches apart and the pipe is placed in the machine so that the joint to be welded is located centrally between these two copper jaws and directly over the copper strip in the backing-bar.

The multiple arc welding process previously mentioned employs two arcs, one following about eight inches behind the other. The two automatic welding heads, used to feed the wire, are mounted on a single motor driven adjustable speed travel carriage, (Fig. 7), which moves the heads along the work at the proper welding speed.

When work was first started on the manufacture of the pipe for the Springfield line, only one travel carriage with two welding heads was used. This carriage, of course, traveled the full length of each 30-ft. seam. A little later, a second travel carriage with two more heads was added. Welding was then carried on simultaneously with four arcs, one carriage starting at one end and the other at about the middle of the seam. This reduced the welding time per pipe by about 50 per cent. It is expected that a third carriage with two more heads will soon be added, each pair then welding about one-

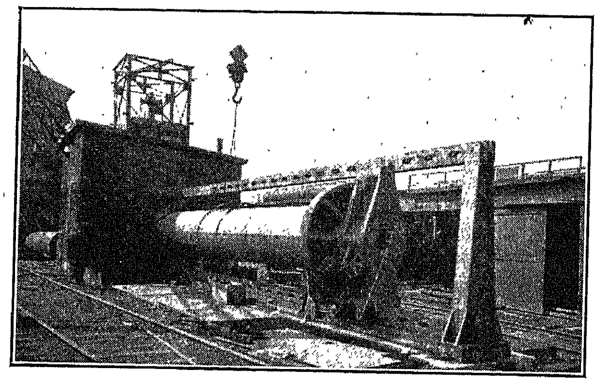

FIG. 8—48-IN. PIPE, 30 FT. LONG FABRICATED FROM TWO ½-IN. PLATES BY AUTOMATIC ARC WELDING UNDERGOING HYDROSTATIC PRESSURE TEST OF 240 LB.

third the total pipe length with corresponding reduction in welding time.

After one seam is completely welded, the pneumatic clamp is released and the pipe is rotated to bring the second joint into position for welding.

SPEED OF WELDING; ELECTRODE AND POWER CONSUMPTION

The speed of welding attained by the multiple arc process with two welding heads on ½-in. plate is about 22½ ft. per hour. Using approximately 380 amperes on the first arc and 330 amperes on the second, the total consumption of 3/16-in. electrode is from 0.8 to 0.85 lb. per foot of weld. These welding currents are somewhat different from those used when the test plates were welded, but were found to give better results on the joint between the two sections of pipe. Current for each pair of welding heads is obtained from a 1000-ampere 1-hr. rated constant potential welding generator driven by an induction motor. The power consumed is approximately 2.15 kw-hr. per foot of weld on ½-in. thick plate.

Inspection and Tests of Welds

At the request of the inspector, test plates having a bevel as specified for the pipe joints are placed in the machine and welded under the same conditions as the pipe itself. These plates are then cut into specimens and tested.

The extent to which the weld is reinforced, that is, its height above the surface of the plate, is usually from 1/16 to 1/8 in. The minimum and maximum values permitted by good practise are 1/32 and 3/16 in. respectively. The weld bead must not be less than 5/8 in. nor more than 1 in. in width and must also be central within 1/16 in. between the lines scribed on the plate each side of the joint. Any holes which are seen on the top surface of the deposited metal are carefully chipped and if they extend below the surface of the plate, the spot is rewelded by hand. The edges of the bead are also examined to see that the weld metal is thoroughly fused along the top of the plate. Any cracks or hollow spots are chipped and rewelded by hand.

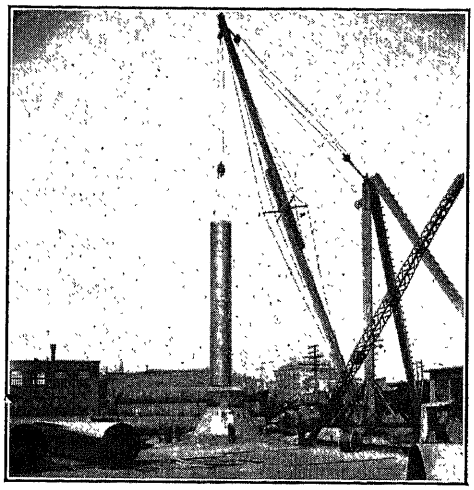

Fig. 9—30 Ft. Section of 48-In. Pipe About to be Lowered into Electrically Heated Vertical Dipping Tank to Receive Protective Coating of Coal Tar Pitch Varnish

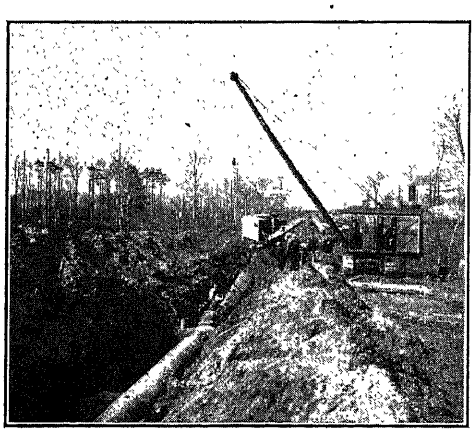

Fig. 10—Laying of Steel Pipe Line for Springfield, Mass., Water Supply. 30-Ft. Longitudinal Joints are Automatically Arc Welded. Circumferential Joints Made in the Field are Riveted

To determine the amount of penetration, the under side of the welded joint is carefully examined. It is necessary that the metal be so thoroughly fused that no crack can be seen between the edges of the plate.

After the welded pipe has been given a careful visual inspection and any defects rewelded, it is placed in the testing machine, (Fig. 8), and subjected to the following hydrostatic pressures in pounds per square inch:

Thickness of pipe in inches	5/16	3/8	7/16	1/2
66-in. pipe	..	160	..	..
54-in. pipe	135	160	187	213
48-in. pipe	..	..	210	240
36-in. pipe	..	..	..	320

Dipping and Laying the Pipe

The rivet holes are then punched in each end of the pipe after which it is thoroughly cleaned and dipped vertically in an electrically heated tank of coal tar pitch varnish, (Fig. 9). The pipe is submerged in the bath long enough to heat the metal uniformly to the temperature of the bath. It is then removed and suspended in a vertical position until the coating has drained and set.

The pipe is then ready for transporting to the field and laying in the trench, (Fig. 10). After the pipes have been properly placed and connected by temporarily bolting, the circumferential joints are riveted and caulked. The middle portion of each length of pipe is then backfilled but the field joints are left exposed until the line has been tested for tightness.

Conclusion

At the time this paper was written, approximately three miles of pipe had been delivered to the field, and its installation in the trench was progressing rapidly.

The advantages gained by the electric welding of pipe as compared with other methods of manufacture are a very substantial reduction in cost and a superior finished product. The reduction in cost is secured not alone by the decreased weight of steel required but also by a reduction in the cost of the actual work of fabricating the pipe.

Owing to the smooth interior of the welded pipe as compared with the riveted pipe, the resistance to flow is decreased. The circumferential joints are made more easily with welded pipe because of uniform wall thickness whereas with riveted pipe the wall is of double thickness at the riveted joint. The joining of the ends of pipe made by the lock bar process is rendered difficult owing to the presence of the bar.

Arc welded pipe is also invading the field of lap welded pipe produced by the lap weld mills because of the fact that the thickness of the wall of the latter is fixed and often times the pressures are such that much lighter arc welded pipe can be used with consequent reduction in the cost of the line.

Discussion

J. F. Lincoln: Mr. Wright's paper is extremely interesting because it brings out a second successful method for doing this sort of work by the electric arc.

The outstanding example of pipe welding up to this time is the Mokelumne River line, 90 mi. in length and containing 78,000 tons of steel. This line has been completed now for some months. This was done with the carbon-arc process instead of the metallic-arc process as is the case in this smaller line described by Mr. Wright.

It is interesting to compare the results as actually obtained in the Mokelumne River line and that described by Mr. Wright. The steel used in both cases was identical—the tests made of the specimens would show approximately the same results.

The welding speed per arc is slightly higher in the case of the Mokelumne River line by not more than 20 per cent. The cost of doing the welding is somewhat less in the case of the Mokelumne River line because of higher speed, because of cheaper filling material, and because of less power used.

In the case of the Mokelumne River line the hydrostatic tests were approximately 60 per cent higher than in the case of the line described. There was also added, in the case of the Mokelumne River line, a hammer test which is much more severe than the hydrostatic test. This hammer test was applied with a tensile stress on the metal itself in excess of 22,500 lb., and an ultimate test running up to a maximum of 28,000 lb., the tensile test in this case being nearly double that used in the line described.

There has been a good deal of progress made in the application of carbon-arc welding since the manufacture of the Mokelumne River line. Since that time the new development of the "electronic tornado" has more than doubled speeds, has eliminated practically all tendency to porosity which heretofore was present in all cases on both the carbon and metallic electrode welding of thick plate, and it has practically eliminated any necessity for repairing. Welding speeds of a single head in excess of one foot per minute on half-inch plate, and with double heads welding speeds of double that, have been obtained. The welds can be bent flat on themselves without rupture and the ductility of the weld metal is fully as great as the ductility of the plate itself.

I think it is safe to say that as far as the welding is concerned in the manufacture of pipe, all necessary development has been done. There is still much to be desired in the planing, crimping, rolling, and assembly of the plates before welding, which progress will enormously reduce manufacturing costs.

At the present time it probably is true that the cost of welding of the pipe itself is less than 1 per cent of the total cost of the pipe, so that any further progress in welding cost reduction is of little moment compared to the cost reduction possible in the operations other than welding.

J. C. Lincoln: The pipe described in Mr. Wright's paper has one end larger than the other so the small end will telescope into the larger end and the ends are riveted as described in the paper. I imagine the inside ends are probably flat-riveted so as to decrease the eddy that would result from the ordinary round-head rivet.

In any case there will be a very considerable eddy at the joint. The metal is ⅜ or ½ in. thick and all around the pipe there is bound to be an eddy. Mr. Day of the United States Reclamation Service was telling of difficulty which he experienced where eddies were encountered in pipe, and Mr. Imlay of the Niagara Falls Power Company says they have had the same difficulty at Niagara Falls. Where there is a severe eddy, apparently a chemical action takes place, eating out the pipe at that point. In the case Mr. Day described to me, a cast-iron pipe 2 in. thick is corroded so that it has to be replaced or repaired in the very near future.

Mr. Imlay said that on their wheels at Niagara Falls repairs of the same sort had to be made as one of the regular upkeep operations.

It seems to me that is a possible criticism of this method of joining pipe though that has nothing to do with Mr. Wright's paper. It won't be very long, I think, before pipe will be joined, not by riveting, but by welding, and if the pipe is joined by welding there will be no special trouble in making a butt weld in which the ends of the pipe will be beveled and so welded as to leave the inside of the pipe smooth and thus avoid this eddy.

R. E. Barnard: I am chief engineer of the Hardesty Manufacturing Company of Denver, manufacturing electric-arc-welded pipe. The particular defect in riveted pipe called to your attention by Mr. Lincoln constituted the main reason for our making electric-welded pipe instead of riveted. In order to eliminate erosive action at the joint we have for several years made a special type of slip-joint pipe in which a collar is electrically welded to one end of a constant-diameter tube and this collar forms the bell into which the spigot end of the abutting section is driven. The result is a smooth interior pipe of the slip-joint type and eliminates the particular destructive action to which reference has been made. We have just completed near Yoder, Wyoming, an electric-arc-welded line entirely field-welded. It is 72 in. in diameter, ¼ in. thick, and made with field joints butt-welded. The plates were 6 ft. long, and the field sections 12 ft. long.

The line is about 900 ft. long and has two elbows in the vertical plane, each of about seven degrees deflection. The only expansion joints in the line are at the ends where special transition sections are imbedded in the inlet and outlet.

This 72-in. pipe is made by very nearly the same process as described in the paper, except that the plate edges are not beveled. The quarter-inch plate, not beveled, is fused through with the Lincoln type of machine without difficulty. For making the longitudinal seam we use the automatically controlled and driven Lincoln arc operating over a clamp similar to the one shown in the paper, only not so large. Circumferential seams are automatically welded by the General Electric metallic arc welder operating over a revolving clamp. All shop welding is automatically done and the field joints made by hand acetylene-gas welding.

H. J. Lawson: We have had considerable experience on the Salt River project with welding on repairs of the electrical machinery and other machinery used in the maintenance of the power system and the irrigation system. Especially we have had considerable experience in repairing runners and water wheels on which there was pitting and erosion. Bronze runners are very easily repaired in that manner.

We took one runner out of a 7500-hp. wheel. It was pitted only slightly but we took it out because one vane in the runner was thin. It must have come from the factory that way originally. It has been in operation about 14 years before there was any necessity of thickening the vane. We took out the wheel and built up that particular vane from less than ¼ in. thick to ⅜ in. and made a successful job of it. While doing that we filled up the pitted places on the back side of the vanes. We also built up by welding, the outside periphery of the wheel where the water wear had taken place, and turned it down to proper size. It was then carefully balanced, after which it was practically as good as a new runner.

In repairs of heavy equipment, excavating machines, etc., where there is excessive wear on steel pins and bearings, especially pins that are quite heavy and expensive, we found that welding saves money and gets the job done quickly.

We also have had considerable experience in welding the shafts of turbines where they have cut and grooved within the stuffing boxes. In every case where we repaired them in that manner we have had no further trouble from the part that was welded. The welding has all been done by electric arc.

C. M. Day: The particular problem of the Bureau of Reclamation relates to cavitation in cast-iron pipes through which water is discharged under high heads, and at high velocities, from reservoirs. At Arrowrock Dam, on the Boise Project, Idaho, we have 20 58-in. balanced valves mounted on the upstream face of the dam, with 54-in. cast-iron pipes embedded in the concrete dam, and the discharge from each valve may be 800 cu. ft. per sec., resulting in a velocity of 50 ft. per sec.

The jet of water, immediately below the valve, is smaller than the pipe, but as the pipe is completely filled within a short distance, and the water velocity is high, a vacuum exists in the unfilled space, which seems to induce a chemical action, perhaps oxidation, which destroys the metal in the cast-iron conduit. This cannot be erosion as the water is not in contact with the metal. These valves and conduits have been installed about 13 years, and at the top and bottom of the pipes, where the shell is 2 in. thick, the metal has almost disappeared in places.

Our problem is to restore the pipes to practically their original condition. We have tried cement grout and lead, but it will not last throughout one season, and arc welding seems to be the only solution. It seems impractical to remove all of the existing metal throughout the affected area by chipping it out, but it is expected to chisel out at least enough to leave perhaps 50 per cent of the area with clean metal. It is expected that each conduit will require at least 400 lb. of new metal, half of which must be deposited overhead.

It has been suggested that copper or bronze, which resists cavitation much better than steel, be used, but to date we have not found anyone who can successfully deposit these metals in a proper manner.

In a similar valve installation at Pathfinder Dam, where the conduits below the valves were lined with ⅜-in. steel plates, with the rivets countersunk on the inside, any rivet head that projected even 1/16-in. caused this cavitation along the surface of the pipe for at least 8-in. below the rivet, where the vacuum would be caused by the exceedingly high velocity of the water, and in this area the pipe shell would be gradually eaten through This action was so rapid and serious that after two or three seasons' use it was necessary to remove the plate-steel linings, and line the conduits with rich concrete grout, with 24 1.5-in. air-vent pipes embedded in the concrete lining, extending to the point where cavitation existed, to break the vacuum. This method seems to have solved the problem at Pathfinder Dam.

At Arrowrock Dam I am confronted with a large repair problem, and will be very grateful for any suggestions as to how to overcome the trouble and replace the lost metal with new metal that will make a satisfactory bond.

J. D. Wright: I should like to inquire why Mr. Day feels that this is a chemical action in what he describes as a vacuum. It would seem to me as though it would be an erosive action at the place where the water enters the cast-iron pipe. I don't see how it can be a chemical action in the vacuum.

C. M. Day: I have never seen a complete explanation. In the first place, where cavitation exists the water is at no time in contact with the metal, and for this reason it has always been assumed that the action must be chemical. Because of the conditions of installation it has been impossible to get close enough to make an investigation.

H. J. Lawson: At the Roosevelt Dam we have had the same trouble, that is, the pitting of the water wheels. It is commonly known that in a partial vacuum oxidation occurs very rapidly and that this action is simply an oxidation or very rapid rusting.

J. H. McCabe: Has there been any development in electric welding of airplane fuselage where they use drawn-steel tubing about 18 or 20 gage? A plant in Colorado Springs is using that type of construction and we have never been able to convince them that the electric arc welding may be used satisfactorily. They employ gas welding.

J. D. Wright: I understand that there is a concern on the West Coast, the Boehing Air Transport Company, which is using the metallic welding process in the manufacture of airplane fuselage.

Ordinarily a thin-gage metal is difficult to weld if it is not properly backed up but a skillful operator, with low welding currents, might be able to do it. Whether or not the Boehing Company does it I can't say.

On that gage the current might be from 25 amperes to 75 amperes.

J. C. Lincoln: I might give a little experience that was recited to me by Mr. Imlay of the Niagara Falls Power Company. He said that in their plant they had a situation where the pipe was pitting and a hole developed inside the pipe. They drilled the hole out and inserted a lead plug. Subsequently the steel has been eroded all around the lead plug though the plug has not been worn away.

This seems to demonstrate quite completely that this is chemical and not mechanical action. You would expect a lead plug to be eroded much more rapidly than steel pipe under mechanical action.

Utilization of Lodgepole Pine Timber for Poles

BY R. W. LINDSAY[1]

Associate, A. I. E. E.

***Synopsis.**—With an ever increasing demand for poles used in the construction of power and communication lines, new sources of supply must be developed from time to time. Along the Rocky Mountain Range are found large stands of various species of timber suitable for the production of poles and so far not utilized to any appreciable extent. This paper outlines briefly the selection of lodgepole pine timber for this purpose, relates the past experience with such poles used in certain test lines, and describes in general the production and preservative treatment of the poles.*

* * * * *

Introduction

DURING recent years the demand for poles to be used in constructing telephone, telegraph, signal, light, and power lines has increased rapidly. In the eastern part of the United States the cedar stands of Maine have been largely depleted of timber of sufficient size to produce long and large sized poles, and the northern white cedar stands of the Great Lakes region are facing the same situation. Although the blight of the chestnut timber in the Appalachian region has somewhat stimulated the current production of chestnut poles, a large curtailment of the future supply of these poles is inevitable. In all pole producing areas, including the enormous stands of red cedar timber throughout the western coast regions and in the southern pine stands of the South, the hauls are becoming longer, and the charges for stumpage are likely to increase from time to time.

In the face of these conditions, and looking into the future, it has been felt that sooner or later it would be necessary to develop a satisfactory substitute for wooden poles or that new sources of supply must be found. To date, substitutes for wooden poles have not been found to be altogether satisfactory or economical, and it is therefore logical for companies serving the public in sparsely settled territory, necessitating heavy expenditures for pole plant, to look for new sources of pole supply, not only for present consumption but to protect their growing demands of the future.

It has been known for a long time that the Rocky Mountain Range, from New Mexico in the South to Montana in the North, is covered with timber of the proper size to make poles, the principal species available being lodgepole pine, Engelmann spruce, western yellow pine, and Douglas fir. There are various reasons why this timber has not thus far produced many poles, but the chief reason is probably the fact that when these species, with the exception of Douglas fir, are placed in the ground they do not resist the attack of fungi to any great extent. Therefore, it has been recognized that unless a satisfactory treatment could be developed to protect the wood from the infection of fungi, the vast amount of pole timber close at hand could not be economically utilized.

In 1923 an investigation was undertaken by the Mountain States Telephone and Telegraph Company to determine (1) whether or not satisfactory poles could be obtained from the native timber, and (2) whether or not a reliable preservative method could be developed to protect the poles after being placed in the ground. In order to decide whether or not satisfactory poles could be obtained from the native timber, three major questions had to be definitely determined:

a. Whether or not suitable pole-making timber could be found in large quantities in accessible places and close to the railroad.

b. Whether or not, from the standpoints of strength, shape, grain, etc., the timber would be satisfactory.

c. Whether or not poles from this timber could be produced at prices equal to or lower than current prices of other poles.

Available Pole Timber

Recent surveys made by the United States Forest Service show the following approximate number of poles that could be produced per acre on certain test sections in several of the national forests of Colorado and Wyoming:

Arapahoe Forest	137 per acre
Gunnison Forest	62 per acre
Cochetopa Forest	47 per acre
Leadville Forest	68 per acre
White River Forest	53 per acre
Medicine Bow Forest	176 per acre

From sections that have been cut for the purpose of securing ties, sawlogs, props, and poles, and in other sections where special surveys have been made, it has been possible to gain a general idea of the proportion of available poles to the total number of sawlogs and ties that this timber affords. The amount of sawlog and tie timber available in the Colorado and Wyoming National Forests (Wyoming and Teton National Forests in Wyoming not included) is as follows:

Species	No. of Feet-Board Measure
Lodgepole pine	10,599,078,000
Engelmann spruce	15,236,420,000
Western yellow pine	2,031,688,000
Douglas fir	1,959,289,000

From the above information, and allowing fully for

1. General Engineering Department, The Mountain States Telephone and Telegraph Co., Denver, Colo.

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trees that would not make satisfactory poles, it can be conservatively estimated that there are now in the Colorado and Wyoming National Forests 200,000,000 trees that would make specification poles. These poles range from 20 ft. to 85 ft. in length with the majority under 50 ft. in length. Besides this growth there is an enormous amount of privately owned pole-sized timber here and there along the range. The States of Montana and Idaho also have very large stands of available pole timber on United States national forests. In Colorado, Wyoming, Montana, and Idaho, this timber, consisting mostly of lodgepole pine and Engelmann spruce, can be secured in large quantities within two to ten miles of

FIG. 1—LODGEPOLE PINE STAND, LEADVILLE NATIONAL FOREST, COLORADO

existing railroad shipping points which are connected with transcontinental railroads, thus making possible comparatively short hauls.

The timber controlled by the United States Forest Service will always be productive of poles in very large quantities. The cutting is so programmed that the mature timber is cut first, the less mature next, and so on until the crop is either materially thinned or entirely cut. The age of the present mature stands varies from 75 to 300 years. Lodgepole pine reseeds itself, and after being cut a new growth appears in a short time. Reproduction or second growth in pole sizes can be obtained within 75 to 100 years, depending upon the soil characteristics, growing conditions, etc.

These forests contain a large amount of Douglas fir or red spruce timber, and, because of its fungi resistant properties, this variety of timber has been used in the past for railroad ties, mine props, and poles, and found to be very satisfactory. At the present time, however, the stands are located in more or less inaccessible sections and the growth is often scattered. In view of these facts, Douglas fir poles would now cost more than poles cut from either lodgepole pine or Engelmann spruce.

TIMBER CHARACTERISTICS AND TESTS

In selecting pole material, the fiber strength in bending is a very important consideration. The strength of pole timber is usually determined by testing the poles in a device by means of which the load, distances from the load to the supports, and the deflections can be accurately measured; and practically all tests of lodgepole pine timber have been made in a standard laboratory testing machine.

Comparative tests[2] of lodgepole pine, Engelmann spruce, and cedar poles were made in 1911 at the University of Colorado, Boulder, Colorado, by Norman Betts and A. L. Heim, engineers in forest products. Twenty western red cedar poles, which were cut near Edgemore, Idaho, and purchased on the Denver market; 22 lodgepole pine poles, cut in the Deerlodge National Forest, Montana; besides 20 lodgepole pine poles and 20 Engelmann spruce poles, fire-killed ten years and cut in Colorado, were all shipped to the University of Colorado for these tests. The strength in bending was determined by placing the poles in a Riehle testing machine and applying a load until failure occurred, and the fiber stress at elastic limit, modulus of rupture, stiffness factor, and modulus of elastic resilience were determined for all poles considered. In addition, the moisture content, annual rings per inch, proportion of heartwood and sapwood, and the weight per cubic foot were determined. The general results of these tests were as follows:

1. Air-seasoned lodgepole pine is superior to western red cedar in all the mechanical properties determined.
2. Fire-killed lodgepole pine is only 80 per cent as strong as western red cedar at maximum load.
3. Fire-killed Engelmann spruce poles are inferior to cedar and pine in all mechanical properties.

The comparative average strength of the cedar, air-seasoned and fire-killed lodgepole pine, and the fire-killed Engelmann spruce is shown clearly in the following table:

	Moisture Content	Pounds/Sq. In. Modulus of Rupture	Pounds/Sq. In. Fiber Stress at Elastic Limit
Western red cedar.......	15.1	6,885	4,430
Lodgepole pine (air-seasoned)..........	21.9	7,680	5,280
Lodgepole pine (fire-killed)..............	16.9	5,481	4,327
Engelmann spruce (fire-killed).............	16.3	4,378	3,489

In 1926 the Mountain States Telephone and Telegraph Company made similar tests of 53 lodgepole pine poles. All the poles were cut green in the Sargents, Pitkin, and La Veta Pass districts of Colorado. Thirty-

2. This report is covered in detail by *Bulletin No. 67*, U. S. Dept. of Agriculture, dated March 17, 1914.

one of the poles tested were open tank-treated with creosote, the temperature of the hot bath during the creosote treatment having ranged between 200 deg. and 260 deg. fahr. These poles were shipped to the University of Colorado, at Boulder, and there tested in the same Riehle machine that was used by Betts and Heim in 1911. To determine the modulus of rupture, the poles were placed in the machine in 20-ft. lengths in order to allow both ends of the pole to rest on the bed of the machine. The load was applied at a uniform speed of approximately one in. per min. The deflection of the pole was noted at intervals of 1000 lb. until a total load of 6000 lb. was reached, after which the machine was kept in balance, the deflection being noted at 250 lb. intervals until failure occurred. The characteristics of each fracture were carefully examined, and data were tabulated regarding the relative location of large knots, the type of fracture and whether or not the pole failed in tension or compression. In the tests the annual rings per inch, twist in grain per 20 ft., taper,

Fig. 2—Riehle Testing Machine at University of Colorado

moisture content, and specific gravity were also determined.

The main conclusions drawn from these tests were as follows:

1. The open tank treatment of the poles did not show a positive tendency either for increasing or decreasing the strength of the pole.
2. A slight tendency toward an increase of strength with a decrease in moisture content was noted.
3. Large knots or rings of knots were found very objectionable from the standpoint of strength.
4. The modulus of rupture for the 53 pieces averaged 7723 lb. per sq. in. The average moisture content was 15.98 per cent.

Among those who witnessed these tests were Messrs. H. N. Biggle and S. E. Horton of the Western Union Telegraph Company, Professors H. J. Gilkey and Clarence L. Eckel of the University of Colorado, and Professor W. C. Huntington of the University of Illinois. In this work the University of Colorado heartily cooperated with and assisted the telephone company representatives, as well as providing the mechanical laboratory and the necessary space in the chemical laboratory for the tests.

In 1927 the Bell Telephone Laboratories made tests of pressure-treated creosoted lodgepole pine poles at the University of Colorado. The average modulus of rupture determined in these tests was 6214 lb. per sq. in.

When considered as to shape, grain, and other physical characteristics necessary for satisfactory pole material, all species,—that is, Engelmann spruce, lodgepole pine, Douglas fir, and western yellow pine, would qualify and would rank in the order named in so far as desirability is concerned. This rating is determined by an examination of the timber after it is cut into poles, noting the taper, the size of knots, the twist in grain, the thickness of sapwood, the extent of undesirable scars, and other features inherent in its growth. Western yellow pine grows generally in rather open areas, is found in large trees and has large knots; moreover, extensive pole producing areas are scarce.

Production Costs

At the time this investigation was made, all cost figures as to stumpage, cutting, skidding, hauling, and loading poles on the cars indicated that poles in most of the available Rocky Mountain areas could be produced at equal or less cost than those shipped in from other sources of pole supply, with the possible exception of southern yellow pine in some districts.

In connection with the cost of producing poles in this territory, the freight factor is very important. For example, poles can be delivered in Colorado from the pole producing areas of either Colorado or Wyoming at a freight rate less than one-half the rate from other sources.

Lodgepole Pine and Experimental Lines

The lodgepole pine, because of its existence in such large quantities and in such favorable locations from a cutting and shipping standpoint, and also due to its greater fiber strength than that of the Engelmann spruce, was chosen as a logical pole timber with which to experiment.

It was recognized that the successful and profitable utilization of lodgepole pine timber for poles could not be expected unless a satisfactory treatment could be employed that would be effective in protecting the wood from rotting after the poles were placed in the ground; and it is now an established fact that this timber can be so protected, as shown by experience with the following lines.

In 1909 at Norrie, Colorado, 1022 fire-killed lodgepole pine poles were butt-treated with creosote oil. The treatment consisted in placing them in a vat containing the oil, which was heated for a sufficient time, allowed to cool and then drawn off. In this process a penetration of from one-eighth inch to one-fourth inch was obtained, which under present day methods is considered shallow penetration. One very important factor which favored these poles was that they were fire-killed and thus perfectly seasoned, and therefore checked very little after they were placed in the lines. Of these poles 561 were placed in service in Rifle, Colo-

rado, by the Rifle Heat and Power Company, and a line was also built extending from Rifle to their power plant, a distance of approximately 12 mi. These poles were inspected in 1917, 1920, and again in 1926. After 17 years' service, 88.4 per cent of the poles were found to be sound, 2.6 per cent contained decay, and 9 per cent had been removed. All tops were inspected and only one pole showed signs of decay above the ground.

In 1910 the Mountain States Telephone and Telegraph Company placed in service 759 poles which were fire-killed and treated at Norrie in the same manner as the poles placed at Rifle. They were used in a line between Hotchkill and Crawford, Colorado, and to this date, after 18 years' service, no replacements have been made, although 42 poles have been reset and 10 have been reinforced.

Studies of pole line inspection reports show that very few poles in the Rocky Mountain territory become infected and rot above the ground line. This is probably due to the lack of moisture necessary to fungi growth. For this reason it is felt that in this territory it is neither necessary nor economical to treat poles above the ground line.

In the light of this past experience, it is reasonably certain that, when seasoned and properly butt-treated with dead oil of coal tar, lodgepole pine poles will prove both satisfactory and economical for the construction of power and communication lines throughout large areas of the West.

Production

Tentative specifications for lodgepole pine poles were drafted in 1924. In general, these specifications followed those for southern yellow pine poles, taking into consideration, however, the characteristics of the lodgepole pine timber. In November, 1926, specifications for lodgepole pine poles and the creosote treatment thereof were drafted by engineers of the American Telephone and Telegraph Company. These specifications were based upon the experience gained in handling, inspecting, and treating these poles and the tests made to determine their strength in bending. These specifications are still in force.

In 1924 arrangements were made with a timber company to cut approximately 10,000 lodgepole pine poles in the vicinity of Sargents and Pitkin, Colorado. Due to the fact that any oil treatment is of little value in this territory unless the poles are properly seasoned, an effort was made to cut these poles so that they would season during the months of June, July, and August previous to their shipment to the treating plant the following January and February. In the seasoning process the moisture content reduces from 60 to 90 per cent to 20 to 25 per cent. The moisture content is determined by removing a core from the pole, drying it in an oven, and calculating the ratio of the loss of moisture to the dry wood. The seasoning is valuable for three reasons:

1. It reduces the weight of the pole, thereby effecting savings in freight and hauling charges.
2. The shrinkage in the wood fiber produces checks which can be stapled and controlled before the pole is treated and placed in service.
3. Poles having a heavy twist tend to straighten out when seasoning. If poles are placed in the line when green, the gains become out of line as the poles season, which, in some cases, necessitates regaining and retying the wires in order to relieve the tension on one side of the arm.

In an endeavor to control the checking of the poles after they have been treated, anti-splitting staples are used for controlling large season checks. These staples are driven into the poles, spanning the checks to prevent further opening. This practise is also employed to control checks in western cedar poles. During the seasoning process small poles shrink from $\frac{3}{4}$ in. to 1 in. in circumference, while large poles shrink from $1\frac{1}{2}$ in. to $2\frac{1}{2}$ in. in circumference, depending upon the size of the pole, the age of the tree, and other factors. It is therefore absolutely necessary that poles be cut from six to nine months in advance of using them, in order that they may be properly seasoned. It is also more economical for the producer to cut poles when the sap is up and the bark can be removed easily, which period is generally between the fifteenth of April and the first of August. All cutting operations, of course, cannot be done during this time, but it is a great aid to the cutter if he can cut and peel a large number of his poles at this opportune time.

In most cutting areas it is more economical to haul the poles from the woods to the railroad on snow with sleds than any other way, although in a few localities, where road conditions permit, probably a wagon or tractor could be operated satisfactorily, but in general such a method is expensive. After being cut, limbed, and peeled, the poles must be skidded to the roads, sorted fairly well according to size and class, and placed on timbers to minimize the chance of becoming infected with fungi growth and to aid in their further seasoning. The weather conditions vary along the range from year to year, and it is generally difficult to haul poles before the first of December following the cutting operation. After snow falls in large enough quantities to permit sledding, the poles are hauled to the railroad and there placed on skids, assorted by classes and lengths to await inspection.

It can readily be seen that it is necessary to program carefully the pole requirements far enough in advance to allow the producer to cut and haul the poles at the most economical time and still have the proper time for seasoning.

Returning to the activities of the Mountain States Telephone and Telegraph Company directed toward determining the feasibility of lodgepole pine pole production, and referring to the arrangements made in 1924 for the cutting at Sargents, Colorado, after these poles

were fairly well seasoned in the woods or at landing yards along the railroad, they were shipped to Salida, Colorado, for treatment.

Preservative Treatment

In the meantime an open tank creosoting plant was constructed at Salida, Colorado, for the purpose of treating poles. Salida was selected as the logical location for this plant, due to the fact that it is near the center of the pole producing timber on the Denver and Rio Grande Western Railroad, and a junction point of the narrow and standard gage routes of this system. The vats of this plant were constructed in general according to plans furnished by the American Telephone and Telegraph Company. There are two treating vats 9 ft. wide, 24 ft. long, and 10 ft. deep. In the bottom of each vat is a steam coil protected by a steel grid. There are two storage tanks for the dead oil of coal tar, one called the cold tank and the other called the hot tank, each containing a heating unit to maintain the oil at the proper temperature. The heating unit in the cold tank maintains the temperature of the oil at approximately 100 deg. fahr. in winter weather and by circulating cold water through this unit during the summer time, the cold oil can be kept at a temperature of approximately 100 deg. fahr. The vats and tanks are supplied with steam from a 40-hp. boiler and under a pressure of 45 lb. per sq. in. A pit is located between the treating vats, in which is mounted a centrifugal pump driven by an electric motor; and the vats, pump, and tanks are connected with eight-inch pipe lines. This arrangement provides for pumping the oil rapidly out of the vat

Fig. 3—Lodgepole Pine Poles in Treating Vats, Salida, Colorado

after the hot treatment and pumping cold oil back into the vat to continue with the cold treatment.

Experiments supervised by the Department of Development and Research of the American Telephone and Telegraph Company were carried out to determine the proper preparation of the poles and the character of the treatment which would produce the best results. In order to insure even and deep penetration, it was found necessary to remove all pink bark on winter cut poles and also the transparent skin on summer peeled poles. The necessary shaving of the poles was done with an ordinary draw knife. It was also found that the most desirable results could be obtained by treating the poles in a hot oil bath for seven hours at a temperature of from 225 to 250 deg. fahr., after which the hot oil was replaced quickly with cold oil and the treatment continued for an additional seven hours at a temperature of from 100 to 110 deg. fahr. With this treatment a penetration of oil was secured ranging from ⅝ in. to 2½ in. with an absorption averaging 2.2 gal. per pole. It was found that by raising the temperature of the hot bath from 225 to 250 deg. fahr. the absorption of oil greatly increased. Tests were made to determine whether or not this heat affected the strength

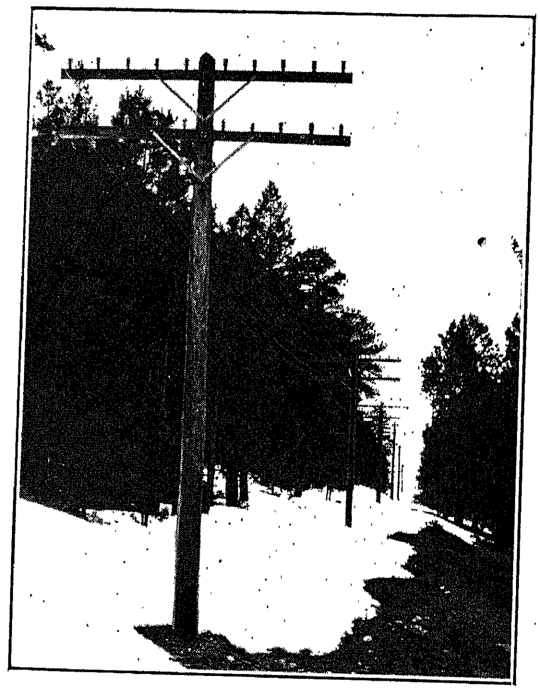

Fig. 4—Lodgepole Pine Pole Lead Near Denver, Colorado

of the pole, and it was found that it did not materially do so.

Test pieces of Douglas fir were treated, and it was found that very little penetration could be secured. Lodgepole pine generally has a thick sapwood while that of Douglas fir is relatively thin. In either species under ideal conditions the sapwood can be penetrated, but very little, if any, penetration can be secured into the heartwood. Tests of fire-killed lodgepole pine timber were made, and it was found that a penetration of more than one-half inch was impossible, regardless of the temperature of the hot bath. In this connection it was impossible to locate stands of suitable fire-killed lodgepole pine in Colorado.

During 1925 approximately 3500 poles were shipped to Salida, where they were prepared for treatment, treated, and reshipped to their destination. The following year 21,000 poles were cut in the vicinity of Sargents, Pitkin, and La Veta Pass, Colorado, treated at Salida and placed in lines in Colorado, Wyoming, and

Utah. In 1927, 16,000 poles were produced in the same locality. In 1927 arrangements were made to expand the production, and contracts were made with a producer on the Moffat Railroad near Phippsburg, Colorado, and one on a branch railroad near Laramie, Wyoming, with the result that the total production in 1928 will be in the neighborhood of 35,000 poles. As the production and consumption of these poles increases, producers should be secured in Montana and Idaho.

Conclusion

There is every reason to believe that tank treated lodgepole pine poles will have an average life in service of at least 15 to 20 years, and possibly longer. There are many factors that affect the ultimate wire load of a telephone pole line, and often this load increases faster than was originally anticipated, with the result that the pole is found to be undersized long before it has been condemned; also, at times other unforeseen factors necessitate moving the pole before its life has been spent. In this territory it now appears that a pole with the lowest possible first cost and a fairly long life is more economical than a pole with a higher first cost and longer life. In other parts of the United States where the density of poles is greater and poles can readily be recovered and reset without damaging the treated portion, different conclusions may be reached.

From the foregoing outline of the investigations thus far made to determine the field of usefulness offered by lodgepole pine timber as a source of pole supply, there can be found justification for continuing and expanding this production, with full confidence that through the employment of proper methods of cutting, seasoning, and treating, lodgepole pine poles will prove highly satisfactory for the construction of the ever increasing number of power and communication lines traversing the western plains and Rocky Mountain region.

Carrier Systems on Long Distance Télephone Lines

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Synopsis.—*A previous Institute paper in 1921 gave a very complete résumé of the activities of the Bell System at that time in the development of multiplex telephone and telegraph systems using carrier-current methods. A new type of carrier telegraph system was subsequently described in an Institute paper. In the present paper the authors describe developments which have resulted in improvements in the carrier telephone art since that time. A new, so-called type "C" system is described in detail, together with suitable repeaters and pilot channel apparatus for insuring the stability of operation: the line problems are considered and typical installations pictured. The growth of the application of carrier telephone systems and their increasingly important part in providing long distance telephone service on open-wire lines are shown.*

* * * * *

INTRODUCTION

AT the Midwinter Convention of the Institute in 1921, Messrs. Colpitts and Blackwell presented a paper entitled *Carrier Current Telephony and Telegraphy*, TRANS. A. I. E. E., Vol. XL, 1921, p. 205. This described the development work of the Bell System which had resulted in the production of commercial types of multiplex telephone and telegraph systems using carrier-current methods. The paper also gave a brief historical summary and included a theoretical discussion of the methods involved, as well as detailed descriptions of apparatus which had found employment in the telephone plant.

The carrier-current art had at that time emerged from the laboratory to play its part in meeting the practical requirements of telephone service in the field. This step was made possible largely by two tools, now indispensable to the communication engineer, the thermionic tube and the wave filter.

In an ordinary telephone circuit, each frequency component in the voice of the speaker is transmitted by an electrical current of the same frequency. In most cases the electrical equipment of the circuit is not called upon to transmit frequencies above about 3000 cycles per sec. In carrier-current operation, however, the voice-frequency currents are caused to modulate a high-frequency current which thus serves as a "carrier" for the message. In this way an additional telephone channel is obtained, using frequencies entirely above those transmitted in connection with the ordinary voice-frequency channel. By using other high frequencies, several additional messages may be transmitted simultaneously on the same pair of wires. Each channel occupies a certain range of high frequencies. For example, the words of one speaker may be conveyed by a channel employing frequencies from about 23,500 to about 26,000 cycles per sec. At the receiving terminal the various incoming ranges of high-frequency currents are separated by electrical filters. Then by demodulation the original voice-frequency currents are produced again and are transmitted over voice-frequency circuits, the transmission over each channel thus reaching the proper listener. In this way a telephone line already carrying d-c. telegraph and voice-frequency telephone services may be multiplexed so as to provide additional telephone facilities. In a somewhat similar manner the high-frequency range may be used instead to transmit telegraph messages. In the present paper, carrier telephony alone is considered.

The Colpitts-Blackwell paper described two carrier telephone systems which had been developed up to that time, a four-channel "carrier suppressed" system (type *A*), and a three-channel "carrier transmitted" system (type *B*). The initial installation of these systems was made about 1918 on the long lines of the Bell System.

These earlier systems were effective in bringing about economies by avoiding the stringing of additional wire on many long pole lines, but there remained many opportunities for further improvement in performance and simplification of equipment. New problems arose to be solved in connection with the desire to operate the largest possible number of systems on the same pole line. The result has been the development of a substantially improved technique and a new system (the type *C*) which not only has provided much improved performance over its predecessors but which has led to further economies because of reduced costs.

Carrier Telephone Growth in Bell System. Whereas the use of the early types of systems was justified in competition with the alternative of additional wire stringing only for distances exceeding 250 to 300 mi., the new system proves economical for distances considerably less. This fact has naturally stimulated the application of carrier telephony in the Bell System. This is shown by Fig. 1, which indicates the growth of these systems in terms of channel mileage afforded by their use. It will be noted that the rate of growth of the systems has increased greatly in the last two or three years, a result of the availability of the improved system.

At the end of 1927 there were in operation about

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28-110

130,000 channel miles. By the end of 1928 the figure is expected to be about 230,000. This figure does not, of course, represent a very large proportion of the total toll mileage of the Bell System, which includes many circuits less than 100 mi. in length. It is sufficient, however, to indicate that the carrier telephone systems are a substantial factor in the provision for the growth of the longer haul facilities, where they naturally provide the greatest economies. Their use is, of course, restricted to sections of the country in which open-wire construction is chiefly employed.[1] They have contributed toward lowering the cost of service and in making possible the toll rate reductions which have been put into effect within the past year or so.

New System Replacing Older Types. The new type *C* system is essentially a long-haul, multi-channel system. It adds three high grade telephone circuits to the facilities normally afforded by a single pair of wires, and can be used over any distances likely to be encountered in the Bell System. Where repeaters are required they are spaced at intervals of 150 to 300 mi., depending upon particular transmission considerations. Stability of transmission over the several carrier channels is assured, despite the relatively large inherent variations in high-frequency line transmission due to weather changes, by means of a pilot channel.

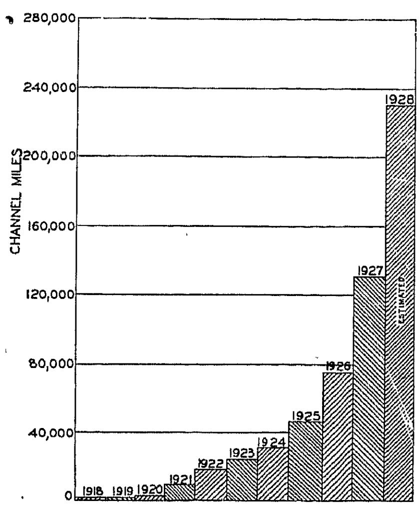

Fig. 1—Growth of Carrier Telephony in Bell System

The service requirements which present themselves in the application of carrier methods are, of course, basically no different from those for commercial talking circuits obtained by other means. The problem is to establish a toll circuit between long distance offices which meets certain standards of transmission, including speech volume, stability, and quality. The latter requires that there must be transmitted a certain band width of frequencies in the voice range. Furthermore, there must exist no appreciable load distortion effects. The circuit must also be relatively free from noise or cross-talk. A signaling system must be provided so that the operators at opposite terminals may call each other. In other respects the system must appear as a normal telephone circuit not distinguishable from an operating standpoint from the other circuits afforded by metallic wire connections. The apparatus installed in the telephone office must conform to certain physical standards of equipment, sturdiness, flexibility, etc. It must be capable of being maintained by trained office forces. Testing facilities must be provided, etc. It is believed that these objectives have been largely realized in the arrangements which are described in this paper.

1. In localities having very heavy traffic requirements such as in the East, extensive use is made of toll cables.

The Type *C* System

The type *C* system embodies those major technical features which our experience with the older systems has indicated as most desirable. It is a carrier-suppressed, single sideband system, in which respect it is similar to the older type *A* system. However, it has been found possible to dispense with the equal frequency spacing of the channels which was characteristic of the type *A* system, and which involved the transmission of a synchronizing current between two terminals and the harmonic generation of higher frequencies from this synchronizing current. A simplification in apparatus has resulted. This non-harmonic arrangement of channels has further made possible a more efficient use of the frequency spectrum by the fact that the channel bands at lower frequencies can be squeezed together more closely than those of the higher frequencies where the band filters are less efficient due to decreasing ratio of band width to frequency.

The type *C* system requires for each modulator an oscillator as a source of carrier supply. Moreover, since a synchronizing current is not employed at the receiving terminal of the channel an oscillator of the same frequency is required for "demodulation." Advances in the art of designing vacuum tube oscillators of great frequency stability have made it possible to insure that these oscillators, which may be hundreds of miles apart, remain sufficiently close together in frequency so that no noticeable impairment in quality of transmission results.

In the matter of the frequency allocation of the channel bands, the type *C* system possesses one of the essential features of the older type *B* system, that is, the use of different carrier frequencies for transmission in opposite directions. Comparative experience with the type *A* system which, by means of high-frequency line and network balance, employed the same frequency band for the opposite directional paths of the channel led to the conclusion that the systems which avoided the high-frequency balance requirement were more desirable. Also the problem of intermediate repeater

amplification is simplified where the opposite directional frequencies are thus separated and grouped. Furthermore, the cross-talk problem between different systems on the same pole line is greatly simplified for reasons which will be discussed later, and a greater total number of channels may usually be obtained on the same pole line.

The single sideband transmission employed reduces by about one half the frequency band that would otherwise be required for each channel. The carrier is not transmitted, as the presence in the system of carrier currents of the large magnitude required for a "carrier transmitted" system not only requires greater amplifier load capacity at the repeaters, but may increase the possibility of troublesome cross talk and noise interference. The selectivity requirements of the band filters would also become more severe to keep the carrier of one channel out of the other channels in the system.

A Complete System. The simplified layout of a complete system is shown in Fig. 2. It will be noted that it includes apparatus at a terminal, a line circuit, a repeater station, a second line circuit, and apparatus at a second terminal. Obviously, the total line length between terminals may be extended by the use of a greater number of repeaters.

At each end there are the terminations of the three carrier channels 1, 2, and 3, and the regular voice circuit 4. These terminations appear, of course, at the long distance switchboard in the same office or in a different office from the carrier terminal. When a subscriber is connected to one of the terminations, for example, No. 1, speech currents pass through the three-winding hybrid coil, thence into the modulator circuit where they are caused to modulate high-frequency carrier current. The resultant modulated bands[2] of frequencies pass through a band filter allowing only the desired band to pass to the transmitting amplifier, thence this band passes through a so-called directional filter and a high-pass filter to the line circuit. The high-pass filter last referred to, in association with its complementary low-pass filter, forms a so-called "line filter" set whereby the regular voice range currents are separated from the higher frequency carrier current at both terminal and repeater offices.

The other two carrier channels function similarly, and the several modulation bands of carrier frequencies join the first channel in passing through the common amplifier and directional filter circuit to the line. At the repeater point the group of bands comprising the three channels passes through the high-pass line filter circuit, thence through a directional filter and line equalizer to the amplifier circuit and outward through the directional and line filter circuit to the next line section. At the farther terminal the combined carrier currents pass through the directional filter and are again amplified in the receiving amplifier. At the output of the amplifier the different carrier channel bands of frequencies are selected one from another by the band filters, thence they pass to the demodulator circuit, are demodulated to their original form and then pass from the output connection of the hybrid coil to their respective terminations.

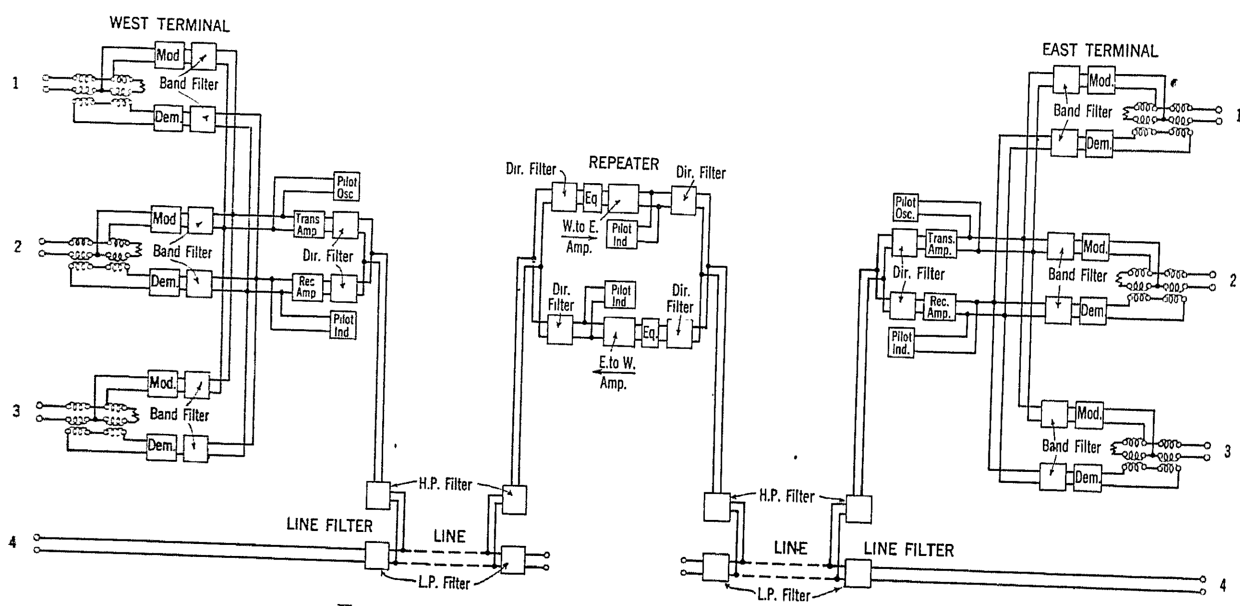

FIG. 2—A COMPLETE CARRIER SYSTEM SCHEMATIC

Circuit Arrangements at Terminals. Fig. 3 shows

2. For a discussion of modulation see E. H. Colpitts and O. B. Blackwell, *Carrier Current Telephony and Telegraphy,* A. I. E. E. TRANS., Vol. XL, 1921, p. 205; R. V. L. Hartley, "Relation of Carrier and Side Bands in Radio Transmission," *Bell System Tech. Jl.*, Vol. 2, April 1923, pp. 90-112.

diagrammatically in somewhat greater detail the terminal of the type *C* system. The modulator circuit consists of a two-tube "push-pull" grid-bias vacuum tube circuit in which the carrier frequency is balanced out. A separate oscillator tube circuit of exceptional frequency stability supplies the carrier. The frequency allocation requires the transmission of only the upper or lower sideband frequencies, and the band filter at the output selects the desired band, rejecting the other products of modulation as well as the amplified voice frequencies which are incidentally transmitted through the modulator unit. This sideband current in conjunction with the corresponding currents of the other two sidebands of the outgoing channels passes through the common amplifier. This is a two-stage vacuum tube unit having four tubes in the output circuit arranged in parallel push-pull connection to insure the required load carrying capacity.

The circuit then leads through a directional filter of either low-pass or high-pass type which distinguishes between the band groups of the opposite directions of transmission as required by the allocation of frequencies. The amplified currents pass through the high-pass filter of the line filter set and thence to the line circuit.

In receiving, the sideband frequencies after separation from the voice currents by the line filter set, pass through the directional filter and an amplifier similar to that used at the transmitting terminal. While the power output required at the receiving amplifier is usually small as compared to that required at the transmitting amplifier, the same unit is used for the two positions to provide flexibility in the adjustments of the receiving gains of the separate channels and for the purpose of economy in production. The different channel currents in the output of the amplifier are selected by the respective receiving band filters and thence pass into the demodulator circuits. In the demodulators the voice frequencies are derived by the modulation of the sideband currents with a carrier frequency supplied by a local oscillator whose frequency is adjusted accurately to agree with that of the corresponding transmitting modulator at the farther terminal. This important problem of synchronization of oscillators is further discussed later in the paper. It is, of course, obvious that if the carrier frequencies of the modulator and the corresponding demodulator of the same channel are not in sufficiently close agreement there will be a serious distortion of the speech currents received over the channel.

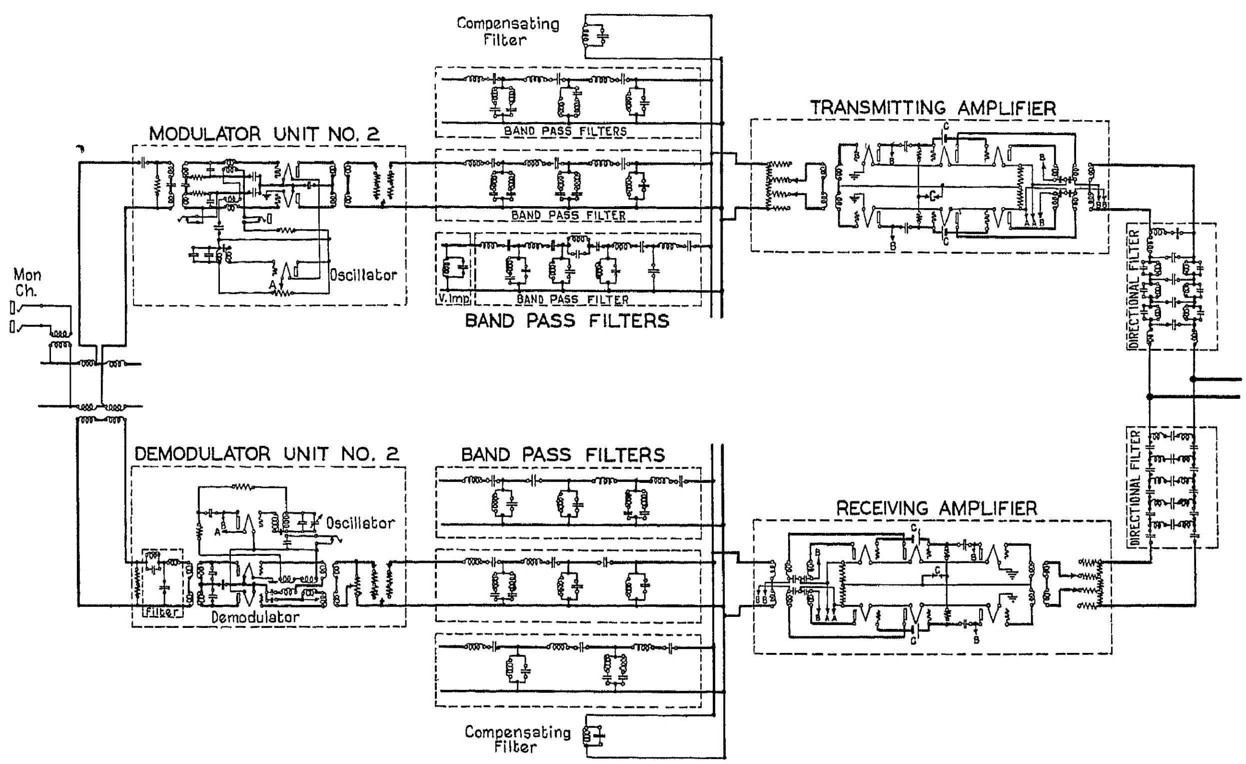

FIG. 3—SCHEMATIC DIAGRAM OF TYPE *C* TERMINAL CIRCUIT

The output of the demodulator circuit includes a low-pass filter for suppressing the unwanted components of demodulation, and the circuit thence leads to the channel terminal through the hybrid coil. The function of the latter is to provide a two-wire termination of the channel and it prevents the output currents of the demodulator from reaching in any substantial magnitude the input of the modulator circuit, thus setting up a regenerative action which might result in "singing."

It may be noted that the circuit normally provides for a transmission "gain" or amplification of energy

from the switchboard termination to the high-frequency line circuit of approximately 20 TU[3] corresponding to a current or voltage amplification of 10 to 1. In the receiving direction a gain of the same order of magnitude is also available. Of course, the exact amount utilized in a particular case depends on the line attenuation and the desired over-all equivalent of the circuit. It is usually desirable at the transmitting terminal to maintain the level at the maximum possible for the system. The over-all transmission afforded by a carrier system may be noted by the curve on Fig. 4, which shows the relative speech frequency transmission characteristics of a typical channel. Where the carrier channel is employed for terminal-to-terminal business the over-all equivalent at 1000 cycles is ordinarily

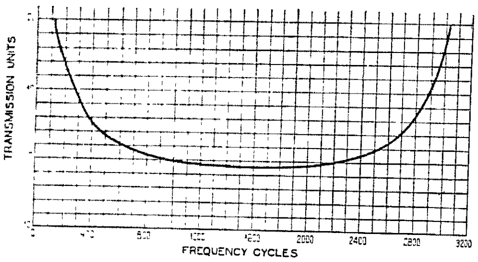

FIG. 4—REPRESENTATIVE OVER-ALL TRANSMISSION-FREQUENCY CHARACTERISTIC—TYPE *C* CARRIER TELEPHONE SYSTEM

adjusted to an equivalent of about 10 TU. The channels not infrequently form sections of much longer over-all circuits, being connected to cable or perhaps open-wire circuits, in which case it is rather common to adjust the carrier section to a zero equivalent or even a gain of several T U.

Line Considerations. The passage of the carrier currents from the terminal apparatus over the line circuit which serves to connect the two terminals, or a terminal and repeater station, gives rise to several problems: the line loss or attenuation, the stability of transmission, the possibilities of cross-talk from other carrier systems on the same pole line, and interference from currents from external sources. These factors must be considered not only in connection with the arrangement of the wires themselves but also in conjunction with the design of the terminal apparatus, repeaters, etc., so that satisfactory over-all speech transmission may result.

As was brought out in the Colpitts-Blackwell paper, the line attenuation at the high frequencies is in accord with the recognized transmission theory. Because of skin effect in the wires and rising losses in the insulators the attenuation increases steadily with frequency. Unfortunately the losses at the insulators are not constant and they increase greatly with the presence of moisture. This brings about an increase in attenuation in rainy weather. Fog, sleet, and wet snow may greatly increase these attenuation changes. There is also a lesser source of variation due to temperature change and its effect on wire resistance.

If care is not taken the carrier currents may be interfered with on the line circuits by cross-talk from other carrier systems and by miscellaneous currents which enter the circuit by induction from the outside. These latter manifest themselves as noise in the carrier channels. This makes it essential to use only the metallic circuit, *i. e.*, two wires well balanced to ground for transmitting the carrier currents. The balance to ground must be maintained at a high degree by frequent transpositions in the wires. Even with these precautions unavoidable residual unbalances may permit a certain amount of interference to appear. The final remedy is to insure that the relations between the circuit length and the apparatus gains are properly considered in order that the speech currents may have ample margin above the noise currents at all points in the circuit.

In the matter of cross-talk between systems closely adjacent on the same line the situation is alleviated by providing two frequency allocations. (See Fig. 5.) These are "staggered" with respect to each other, so that a system installed on one pair using the so-called *N* frequency allocation has less cross-talk to and from a system installed and operating on an adjacent pair and using the so-called *S* frequency allocation than would be

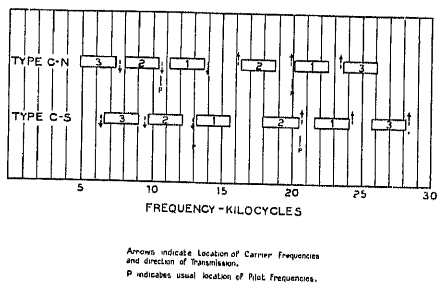

FIG. 5—FREQUENCY ALLOCATIONS OF TYPE *C* SYSTEM

the case if both systems employed the same allocation. The maximum upper frequency required is raised only slightly by this arrangement.

Repeaters. Repeaters must be employed when the distance exceeds that for which terminal transmitting apparatus is effective in maintaining the transmission level well above the line noise. The function of the repeater is, therefore, to amplify the carrier currents so that they pass on to the succeeding line section at a magnitude comparable to that sent out from the terminals. Obviously, the design of the repeater with respect to its gain and level carrying capacity, etc., presents a wide range of possibilities, depending on the distance of transmission, frequency, etc.

3. R. V. L. Hartley, "The Transmission Unit," *Electrical Communication*, Vol. 3, No. 1, July 1924, p. 34; W. H. Martin, *Transmission Unit and Telephone Transmission Reference System*, TRANS. A. I. E. E., Vol. XLVIII, 1924, p. 797, *Bell System Tech. Jl.*, Vol. 3, July 1924, pp. 400-408.

It has been found most practical to install the repeaters along the route at approximately the spacing of the voice-frequency repeaters on the same wires. This means a spacing of from 150 to 300 mi., and occasionally slightly over 300. To have in the same office both voice-frequency and carrier repeaters reduces the equipment, simplifies the maintenance problem, and makes it possible to use the same sources of power supply. The gain and the load carrying capacity are, therefore, determined by this spacing, the gain being controlled by the attenuation loss between the repeaters, and the load carrying capacity by the output level desired because of noise considerations.

The higher attenuation of the line in the carrier range of frequencies means that the carrier repeaters must have a maximum gain of approximately four times that of the voice repeaters operated on the same wires. Whereas gains of the order of 8 to 15 TU may be readily supplied by voice repeaters using balance and so-called "two-wire" operation, the 30 to 45 TU gain required by the carrier repeaters necessitates non-balanced or "four-wire" operation or its equivalent, by using different frequencies in opposite directions and directional filters for the prevention of "singing."

Fig. 6 is a schematic diagram of the circuits comprising a typical repeater station including loading, compositing apparatus, and line filters. After passing through the high-pass line filter the carrier currents arrive at the high and low group directional filters which distinguish between the oppositely directed currents. These filters are substantially the same as those used for similar purposes at the terminal stations.

It is, of course, required in the design of the directional filters that in each direction the filters must pass a frequency band sufficient to transmit properly the three carrier channel bands. In addition to this the filters must present a loss outside of the transmission band which is sufficient to prevent the two-way amplifier circuit from "singing." This means that considering the closed loop circuit of the two amplifiers and the four directional filters the attenuation in this loop must be considerably greater than the sum of the gains or amplification of the two amplifiers. There are also other requirements which these filters must meet which are discussed later.

The amplifiers are the same as used for group amplification purposes at the terminals. Each consists of a two-stage reactance-coupled vacuum tube circuit having four tubes in parallel push-pull connection in the output circuit. The carrying capacity of this amplifier with the standard plate voltages is about one watt in the output, and the over-all amplification or gain including incidental filter losses is about 30 TU. Where gains greater than 30 TU are necessary in the higher frequency group provision is made for the addition of an amplifier stage ahead of the unit shown, which adds approximately 15 TU gain. At the same time provision is made for the addition of greater directional filter selectivity.

An important feature of the repeater circuit is the equalizer which is connected ahead of the amplifier. Because the line circuit attenuation varies with frequency and is greatest at the higher frequencies, it is necessary that the amplification introduced at a repeater

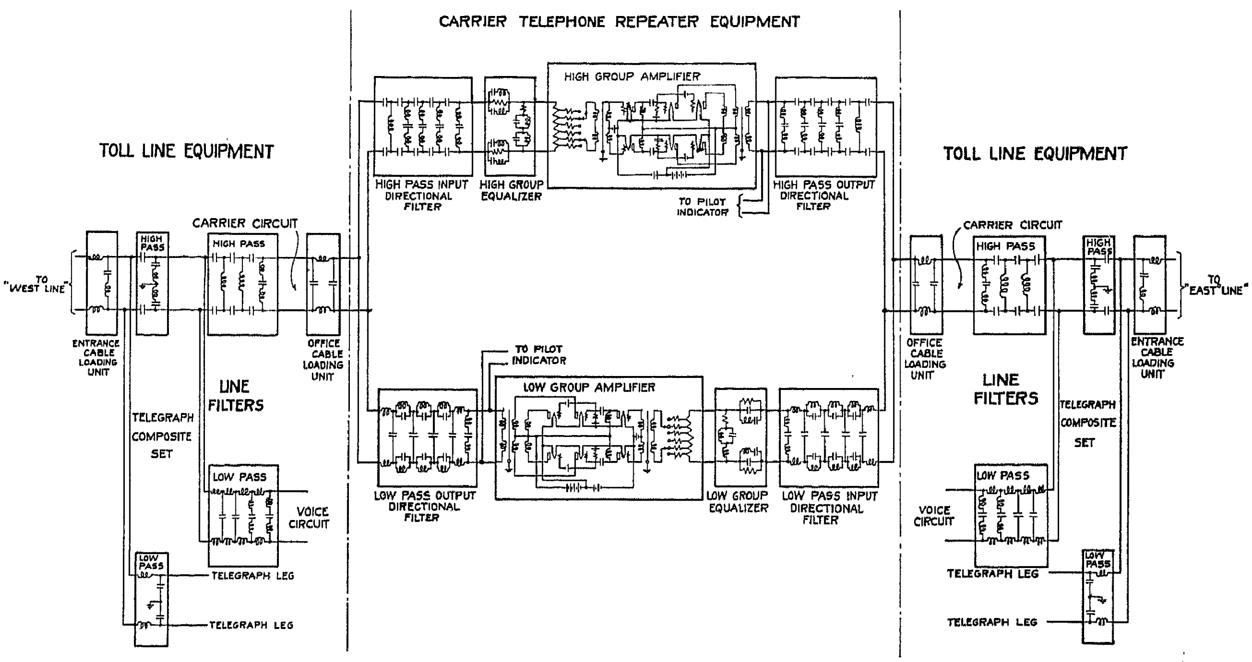

FIG. 6—GENERAL SCHEMATIC OF CARRIER REPEATER CIRCUIT WITH ASSOCIATED LINE EQUIPMENT

point be varied with frequency. The amplification introduced by the amplifier unit itself is substantially uniform with frequency. The equalizer network, however, by introducing a loss which is a minimum at the highest frequency of transmission and which increases for the lower frequencies makes the over-all repeater amplification a function of frequency and in general proportional to the line attenuation which it is designed to overcome.

A typical over-all gain characteristic of the repeater is shown in Fig. 7. The adjustment of the exact

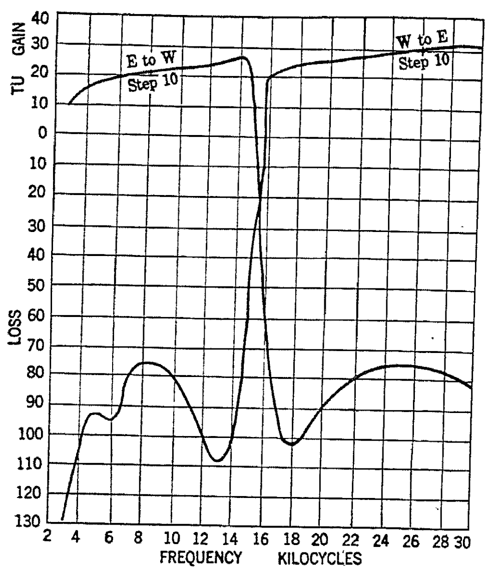

Fig. 7—Over-all Transmission Characteristics of Carrier Telephone Repeater Station

amount of gain desired at any time is made by the potentiometer at the input of the amplifier.

Pilot Channel. As noted previously the attenuation of open-wire circuits of substantial length is affected by weather conditions. This makes it necessary to make occasional gain adjustments throughout the system. The extent of these adjustments is determined by means of the pilot channel which provides a visual indication of the transmission levels of the carrier system in both directions of transmission without interfering with the speech currents over the channels themselves. It is, in effect, a separate constant frequency carrier channel allocated between certain speech channels in each transmission group.

The operation of the pilot is relatively simple. At each repeater point and receiving terminal there appears a meter for registering the output level of the amplifier. The pointer of the meter is expected normally to rest on the zero or normal level layout of the system. If a change in the attenuation of the line circuit causes a departure in the transmission level, the meter reading shows a corresponding "up" or "down" indication and by adjustments of the repeater or terminal amplifier potentiometers the level may be returned to normal. An alarm circuit is furthermore provided at the receiving terminal so that when the level has departed by more than a predetermined amount, say $\pm$ 1.5 TU, from the desired normal, the operating attendant is called in to make the adjustment.

A high-frequency current of constant amplitude is transmitted from each end, and the meter indications are measurements of this current at the output of repeater amplifiers, and at the receiving terminal amplifiers (see Fig. 2). A separate pilot frequency is utilized for each direction of transmission. Because no communication is carried on over this pilot carrier current, the band provided is extremely narrow, and no appreciable portion of the frequency spectrum is sacrificed.

The frequency selected for the pilot channel must coordinate with the other carrier system frequencies. The two frequency allocations of the type *C* system require different pilot channel frequencies because their speech channels occupy different frequency bands. The apparatus has therefore been made so that the frequency of the pilot current can be adjusted to any value desired in the carrier range. The frequency selected for a given system may be determined by local conditions of cross-talk or interference, although in general the preferable location is between the channel bands as noted in Fig. 5. The amount of current which is used is limited by its interfering effect into adjacent channels or into other carrier systems on the same line, and it is ordinarily of a low value, of the order of 2 to 6 milliamperes on the line.

Fig. 8 shows schematically the principal features

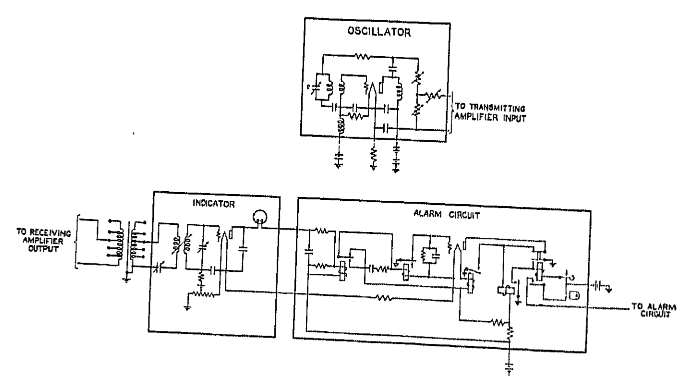

Fig. 8—Schematic of Pilot Channel Circuits. (The Alarm Circuit is used with Terminals Only)

of the terminal pilot-channel circuit as a whole. The oscillator at each transmitting terminal which produces the pilot current is connected to the carrier circuit at the input to the transmitting amplifier, in parallel with the band filters. This current is amplified with the speech currents and transmitted through the directional filter to the line. The attenuated pilot and sideband currents pass from the first section of the line into the receiving directional filter of the first repeater and enter the amplifier. The pilot channel indicator circuit is bridged across the output of the amplifier, and is tuned to

discriminate very sharply against all but current of the pilot frequency. This circuit has a high impedance relative to the line, so that only a very small percentage of the pilot current is drawn from the line at a repeater point. The remainder is transmitted through the outgoing directional filter and over the subsequent section of the line.

That portion of the pilot current which enters the indicator circuit is amplified and rectified in the vacuum tube detector, and the output current is read on a d-c. milliammeter. As stated above this meter is calibrated to read in TU above and below a mid-scale position which represents a normal transmission level to which the system is initially adjusted.

Entering the receiving terminal of the carrier system, the pilot and speech currents pass through the directional filter and are amplified. As at the repeater, the pilot indicator circuit is bridged across the output of the amplifier. At this terminal, in addition to showing level, the output of the indicator actuates an alarm circuit which operates when the transmission level at this point varies from normal for a set interval of time by more than a prescribed amount. This delay action in the operation of the alarm provides selectivity against slight interference into the pilot channel from currents on the other channels of the system and thereby insures that the alarm indicates a definite level change.

The pilot channel thus insures that the high frequency portion of the system is continuously checked with the exception of the individual channel band filters and modulator and demodulator units. These, however, are particularly stable in operation and require no unusual attention in maintenance. Of course, the over-all check is made at only the pilot frequency in each direction. Variations of line equivalent caused by weather changes increase in magnitude with frequency. Therefore, corrections must be made in the gain relations of the individual channels whenever these weather changes are great. Fortunately the corrections follow a fairly definite relation with variations of pilot level and are ordinarily made by the terminal attendants on the channel potentiometers controlling the demodulator gain by reference to a table. This table shows the relations between the required gain changes at the three channel frequencies in terms of changes at the pilot frequency.

The type of oscillator is essentially the same as that used in the type *C* carrier systems for producing the carrier frequencies. It is controlled by condensers which include an adjustable air condenser for tuning to the particular frequency desired.

Two indicators are located at the repeater, one for each direction of transmission. Each indicator circuit consists of a vacuum tube rectifier operating from coupled tuned circuits into a d-c. milliammeter having a special scale calibrated in transmission units. The filament and plate currents and bias potentials are obtained from the standard 130-volt battery. The advantage of using the same battery for the several functions is that it makes possible the stabilization of the rectifier output with power variations. An adjustable grid bias voltage is obtained from the negative drop of the filament circuit with an opposing 3-volt dry cell battery connected in series. With this arrangement normal variations in the 130-volt source cause only a negligible change in the indicator meter readings.

At the receiving terminal, in addition to the indicator circuit which is the same as at the repeater, an alarm circuit is provided as noted above. A sensitive marginal relay is connected in series with the indicator meter. When this relay operates, it starts the delay circuit by removing ground from the grid condensers of the alarm tube. The leakage through the grid resistances then causes the condenser potential, which is the grid potential of an auxiliary rectifier tube operating from the

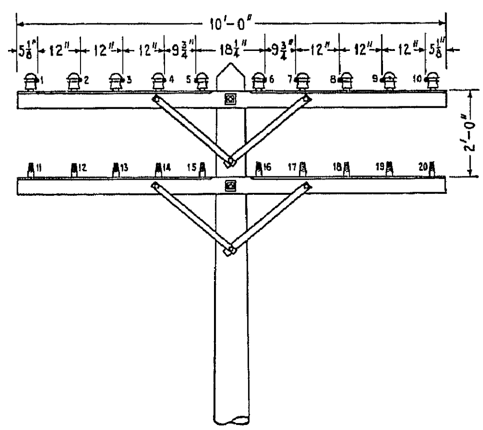

FIG. 9—SHOWING ARRANGEMENT OF WIRES ON TELEPHONE POLE LINE

same power source, to decrease slowly, resulting eventually in a rise in the current of the plate circuit of the alarm rectifier tube. If the marginal relay remains operated for a given length of time, the alarm tube plate current will rise to a value necessary to operate the alarm relays. For shorter periods of operation the normal highly negative grid potential of the rectifier tube is restored and no alarm is operated. The timing of the delay circuit is adjusted by the values of the grid leak resistances and condensers. A delay of about 15 sec. is usually employed which effectually prevents false operation due to occasional transients such as speech interference. The adjustment of the contacts on the alarm relay is ordinarily such as to cause an alarm to be given at limits of $\pm$ 1.5 TU variation.

General Transmission Considerations

Lines. The typical open-wire telephone line consists of a number of 10-ft. crossarms spaced two ft. apart on poles whose height varies from 30 ft. upward depending on local conditions. The poles are spaced at an average interval of 130 ft. Each crossarm carries 10

wires. The wires are normally spaced at 12-in. intervals, except in the case of the so-called pole-pairs which straddle the pole and whose wires are about 18 in. apart. (See Fig. 9.) The construction includes pins and glass insulators for supporting the wires.

There are three gages of wire in common use in the telephone plant, having diameters of 104, 128, and 165 mi., respectively. The largest gage, 165-mil pairs naturally afford the lowest attenuation and have been generally used in connection with the application of the longer systems. The pairs of this sized conductor

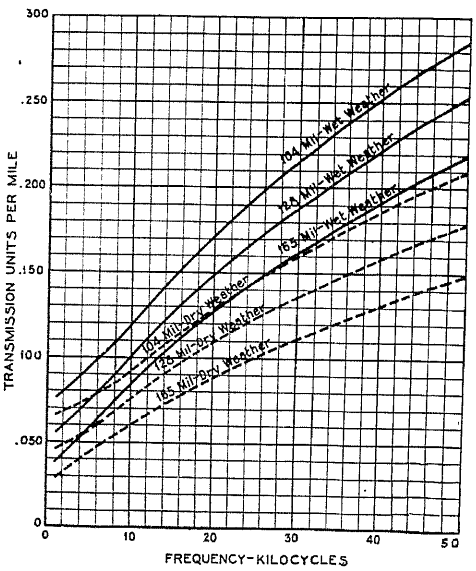

FIG. 10—ATTENUATION CURVES FOR OPEN-WIRE LINES OF DIFFERENT GAGES AT HIGH FREQUENCIES

are, however, now fairly well used up for carrier purposes and new installations are being made more often on the smaller diameter circuits.

Typical attenuation curves for the three gages of wire and the extremes of weather conditions are given in Fig. 10. It will be noted that the wet weather attenuation may be as much as 40 per cent higher than the dry weather attenuation. These variations are greater at the higher frequencies.

It is interesting in this connection to consider the effect of the possible variation in a practical case. Take, for example, a 165-mil pair 200 mi. long with a carrier channel frequency at 25 kilocycles. This means a total attenuation of 20 T U in dry weather and 29 T U in extremely wet weather, a variation of 9 TU or a current ratio of about 3 to 1. In the case of a still longer line these possible variations present rather startling figures. For example, in a 1000-mi. circuit the variation would be five times the above or 45 TU, which would mean that if the circuit were set up to have a proper volume of transmission in dry weather and rain occurred over the whole line it would cause the speech at the receiving end to drop to but 1/180 of the desired volume if the proper readjustments of gain at the repeaters and terminals were not made. Fortunately, these line variations occur gradually, at least in the case of the longer lines.

In connection with most carrier installations measurements are made[4] of line characteristics prior to the installation of the apparatus. An interesting picture is presented in Fig. 11 which shows the attenuation variations with time on a particular line (about 110 mi. in length) during the period in which a storm arose to cause the attenuation to increase. Later, when the insulators had dried off, the corresponding drop in attenuation is evident. From these variations it is quite obvious that means such as afforded by the pilot channel are needed to insure that the talking circuits provided by the carrier channels remain at substantially constant volume.

In addition to the improvement in stability effected by the use of pilot channel apparatus, substantial advances have been made in the design and application of special types of line insulators in which the high-frequency losses, particularly in wet weather, have been appreciably reduced resulting in still further improvement in stability. The attenuation data given above are for the lines equipped with the older standard types

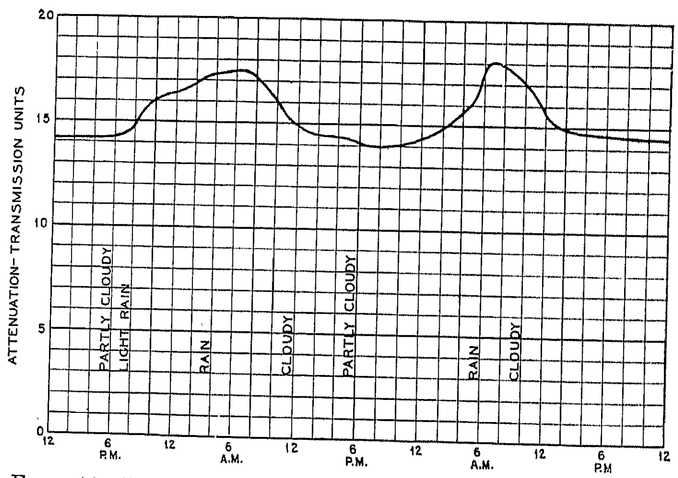

FIG. 11—VARIATIONS IN ATTENUATION OF A PARTICULAR OPEN-WIRE CIRCUIT

of telephone insulators, which are still employed on the majority of circuits in the telephone plant. However, the newer types of improved insulators are now being applied and their use makes it possible to reduce the wet to dry weather attenuation variation by a factor of about 3 to 1 and to reduce the absolute value of attenuation at the higher frequencies by as much as 25 per cent. Further information describing the development work which has made possible these improved insulators will be made available at a later date.

While the circuits employed for the transmission of

4. *High-Frequency Measurements of Communication Lines*, H. A. Affel and J. T. O'Leary, A. I. E. E. TRANSACTIONS, Vol. XLVI, 1927, p. 504.

carrier telephone systems as noted above, are largely of open-wire construction, where these circuits pass through the more populated districts of the country it is frequently necessary to insert sections of cable. The smaller closely spaced wires of cables make the problem of attenuation at high frequencies more serious, even where the cables are relatively short, say a mile or so in length. Typical attenuation curves of non-loaded cable pairs are shown in Fig. 12.

This situation has led to the development of a special type of cable loading which permits making a substantial reduction in the attenuation for the higher frequencies and which also makes the characteristic impedance of the cable circuit more closely simulate that of the open-wire circuit so that the reflection effects discussed in detail later are thus greatly reduced. This is important, for, whereas the open-wire circuit characteristic impedance varies from 600 to 700 ohms, the non-loaded cable impedance is of the order of 130 to 150 ohms and the reflection losses and also certain resultant cross-talk effects as discussed later are therefore

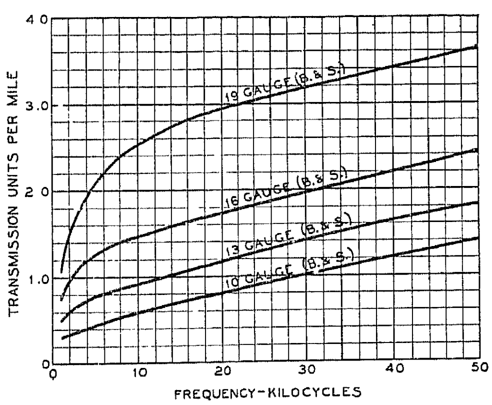

FIG. 12—ATTENUATION OF NON-LOADED CABLE CIRCUITS

very substantial for even short lengths of non-loaded cable. The present standard types of carrier cable loading systems[5] provide for the use of loading coils spaced at intervals of approximately 930 ft. When loaded, the cable circuits have a characteristic impedance loosely approximating the open-wire impedance over the frequency range used in carrier transmission. This same carrier loading also greatly improves the characteristics of the voice circuit. The high-frequency attenuation is reduced to approximately one-half the non-loaded condition. A special type of cable loading is also available for use in improving the transmission characteristics of office cable and wiring and very short intermediate and entrance cable.

External Interference. The carrier channels are unusually free from noise due to extraneous induced currents. This, however, is the result of attention to this factor in the design of the apparatus and in laying out the installations rather than anything inherent in the high-frequency feature as such. Our experience has indicated that it is possible, if care is not taken, to have interference from the following external sources:

a. Harmonics of power frequencies.

b. Irregular frequencies produced by abnormal power line actions, such as arcing insulators, charging lightning arresters of certain types, electric railways, series street lighting, etc.

c. Power line carrier systems.

d. Powerful transoceanic radio transmitters.

e. Lightning and other atmospheric disturbances.

In the matter of harmonics of the power line frequencies, the source of their generation normally limits them to very low magnitudes in the high-frequency range which has been employed for carrier systems on telephone lines. In this respect the carrier systems are, in general, affected to a lesser extent than the normal telephone circuits in the voice range. In the latter case, the power circuit harmonics frequently present serious interference problems because the harmonics in the power circuits are substantially greater at the lower frequencies.

Under particular conditions, however, such as, for example, in connection with a series street lighting system operated with individual series transformers or auto-transformers, where a burned out lamp causes the saturation of the transformer magnetic circuit, induced harmonics of considerable magnitude, up to 30,000 cycles and over, have been measured in the carrier telephone circuits. Under the same conditions, however, much larger harmonics are present in the voice-frequency range, so that the induction in the normal telephone circuit is more severe than the carrier circuit.

A much more severe source of carrier interference has been found to result from the abnormal actions of power line circuits in which arcing phenomena occur. Interference of this sort has been noted and traced to such sources as arcing insulators, tree leaks, pantograph and trolley collector sparking, charging lightning arresters, unusual commutator or slip-ring sparking, switching, etc. In the early days of operation of carrier systems, interference of this type formed a not uncommon source of disturbance. The situation was remedied in some cases by cooperation with the power companies concerned. On the whole, this source of interference has been greatly reduced in the past few years.

On occasions the carrier telephone systems have been interfered with by power line carrier systems operating on near-by power lines. Considering the wide-spread use of power line carrier telephone systems and the fact that they normally involve a transmitting power many times that of the systems described in this paper, this would, no doubt, be a more common source of difficulty were it not for the fact that such power systems adjacent to the telephone systems are operated

5. Thomas Shaw and Wm. Fondiller, "Development and Application of Loading for Telephone Circuits," *Bell System Tech. Jl.*, April 1926, pp. 221-281.

well above the frequency range of the telephone line carrier systems.

Energy picked up from the high-power transoceanic radio telegraph stations, transmitting at frequencies in the carrier range, is an occasional source of interference, particularly in the East where carrier systems are located relatively close to the radio stations. The open-wire telephone lines act as long-wave antennas and intercept the radio energy. This, of course, enters initially on the longitudinal wire circuit to ground. Due to residual line unbalances, some energy is, however, unavoidably passed on to the metallic circuits on which the carrier systems are operated, and enters the speech channel in the form of a tone or note similar to a heterodyne signal at a radio telegraph receiver.

Lightning and general static disturbances form a substantial part of the background noise which is found on all carrier lines. Its general magnitude is ordinarily small, except under certain conditions such as the case of near-by storms.

Transmission Levels. In the design and laying out

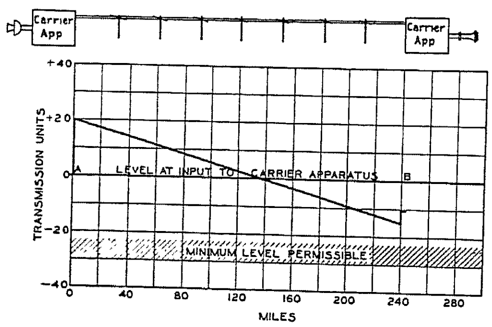

FIG. 13—TRANSMISSION LEVEL DIAGRAM

of type C installations, the transmission level of a system is ordinarily not permitted to fall below a certain figure, which under particular circumstances might be about $-$ 25 TU, with respect to the transmitting terminal. A transmission level diagram will serve to explain this limitation.

Let it be assumed that it is desired to effect carrier transmission using a type C-N system between points A and B, 240 mi. apart on 165-mi. conductors. The highest frequency channel is normally considered, which in this case would be 26 kilocycles. The total attenuation of the line at this frequency, as determined from the line attenuation data already presented, would be 35 TU for wet weather conditions of operation. A level diagram would accordingly picture the situation as noted in Fig. 13. At point A, sufficient transmitting gain would be provided by the equipment to bring the sending level to + 20 TU. The line attenuation in connection with transmission over the 240-mi. circuit at point B would bring the level to $-$ 15 TU. In order to obtain an over-all talking circuit of, say 10 TU, it would be necessary to operate with a receiving gain of 5 TU. It will be noted that in this particular layout the minimum line level is well above the limit set above. In fact, computations would indicate that the line circuit might be extended to the total length of about 300 mi., before the level limits would be exceeded. On longer lines, however, involving many repeater sections, the level limits are raised because of the cumulative effect of noise entering the circuit from a greater number of sources.

The line circuit illustrated is of the simplest type and in a practical case involving sections of intermediate and terminal cable construction, the attenuation would be considerably greater and the effective geographical distance covered for a particular type of apparatus would, therefore, be less.

Cross-talk. Telephone circuits which are simultaneously operating in close proximity on a pole line are normally subject to cross-talk because of the mutual inductance and capacity relations between the wires. The problem which this presents in a pole line structure carrying many circuits requires careful consideration, even where the frequencies are no higher than the voice range. The problem is cared for by the application of transposition systems, *i. e.*, arrangements whereby the effect of these relations between the circuits tends to be canceled out by transposing the wires constituting the two sides of a circuit in an orderly fashion. These transposition systems are carefully designed and the transpositions to be applied in each circuit specified.[6]

When using still higher frequencies for carrier purposes, this problem is correspondingly increased as the mutual relations tend to become greater at higher frequencies. The phase changes as the currents progress along the lines are more rapid for the higher frequencies. The design of the transposition system capable of permitting the simultaneous operation of a number of carrier systems on the same pole line is a difficult problem. The subject is one of great complexity and to give it complete consideration would require more space than is available here. It may be noted, however, that, by means of special transposition layouts installed in the circuits being used for carrier transmission, successful operation is being obtained with a large number of carrier systems on the same pole line, both telephone and telegraph. The locations of transpositions in circuits used for carrier transmission occur more frequently than in circuits restricted to operation at voice frequencies, in some cases as frequently as every other pole.

Several factors in the apparatus design have contributed in lessening the degree of hardship imposed by the cross-talk problem:

1. The standardization of arrangements whereby the same frequencies are only employed in a given direction on systems on the same pole line.

6. H. S. Osborne, *The Design of Transpositions for Parallel Power and Telephone Circuits*, A. I. E. E. TRANSACTIONS, Vol. XXXVII, 1918, p. 897.

2. The equalization of the transmission levels between paralleling systems.

3. The use of "staggered" frequency allocations for systems in closest proximity.

4. A careful consideration of impedance relations in the line circuits and apparatus.

Frequency Directions. The importance of the use of a separate frequency for each direction of transmission may be considered by reference to Fig. 14. If

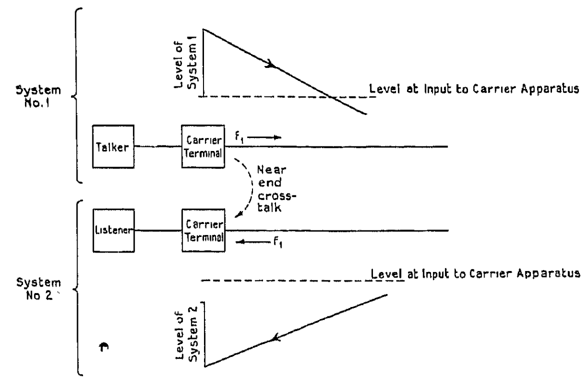

FIG. 14—DIAGRAM ILLUSTRATING OCCURRENCE OF NEAR-END CROSS-TALK BETWEEN CARRIER SYSTEMS EMPLOYING THE SAME FREQUENCY FOR OPPOSITE DIRECTIONS OF TRANSMISSION

there are two paralleling telephone circuits employing frequencies f_1 in the same range, and if there exists between the two circuits a certain amount of cross-talk, when there is a talker at the terminal of one system (No. 1) and a listener at the same terminal of the other system (No. 2), then the speech from the talker at the high level will enter directly into the sensitive receiving circuit of the listener. This is commonly called "near-end" cross-talk. In the case of a carrier circuit, the transmitting terminal would involve a certain amount of amplification. The receiving circuit would likewise, so that the net effect would be that the cross-talk between the two circuits would be amplified by the combined amount of gain or amplification present in the sending and receiving circuits. In telephone parlance it would be stated that this is a situation in which substantial level differences exist between the two circuits.

On the other hand, in the case of two adjacent carrier systems employing the same frequencies for the same direction of transmission, a cross-talk situation involving only "far-end" cross-talk would exist, as illustrated in Fig. 15. This assumes that near-end cross-talk by reflection as discussed later has been eliminated. In this case the talker and the listener would be situated at opposite terminals of the paralleling circuits and the cross-talk, while being amplified like the near-end cross-talk by the total gain in the transmitting and receiving circuits, suffers the attenuation of the line circuit which more than offsets the amplification. This is, therefore, a very substantial factor in favor of the two-frequency method of operation.

At the carrier frequencies, it has been found impracticable to design transposition arrangements providing for systems where the same frequencies are transmitted in opposite directions. It has been found that, while the two-frequency operation may mean fewer two-way operating channels within the same frequency range on a single pair of wires than would be the case if the same frequency bands were provided for opposite directional transmission, the net result in the former case is to make it possible to obtain a greater number of channels on a pole line having many pairs of wires. The need for the directional coordination of frequencies has led to the general adoption of rules throughout the Bell System whereby the systems are all installed so that the low-frequency directional group of channel transmits east to west or north to south and the high, frequency directional group in the reverse direction, west to east or south to north.

Level Equalization. A situation involving an exaggeration of the crosstalk between two paralleling carrier systems may, of course, arise, even in the case of systems involving the transmission of the same frequency in the same direction for the two systems, if the transmission levels of the systems are not the same. If, for example, two systems operating between the same terminals are set up to have the same over-all talking equivalent, and one system has a transmitting gain 10 TU higher than the other, the second system must have 10 TU greater receiving gain in order to provide the same over-all equivalent. This would mean that this system would receive from the first system 10 TU higher crosstalk than if the levels of the two systems were alike. Efforts are therefore made in "lining up" the paralleling systems on a pole line so that as nearly

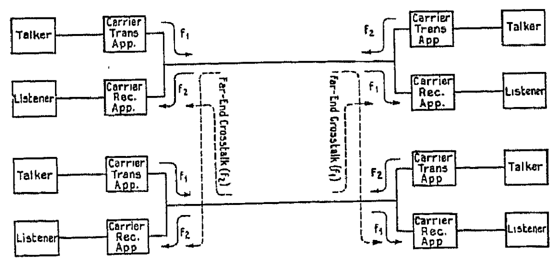

FIG. 15—DIAGRAM ILLUSTRATING OCCURRENCE OF FAR-END CROSS-TALK ONLY IN CARRIER SYSTEMS EMPLOYING DIFFERENT FREQUENCIES FOR OPPOSITE DIRECTIONS OF TRANSMISSION

as possible the same level relations are obtained for all systems, and the crosstalk tendencies are thus minimized.

Staggering of Frequency Bands. A substantial reduction of cross-talk is obtained through the staggering of adjacent system frequency allocation as previously noted. Fig. 5 has shown the frequency allocations of the *C–N* and *C–S* systems. Because present standard types of telephone transmitters and receivers have response characteristics which exhibit the greatest sensitivity in the vicinity of 1000 cycles, as the bands

of two adjacent channels are shifted from an overlapping position, the cross-talk is appreciably reduced. In this case, also, the overlapping cross-talking points are always opposite sidebands and the intelligibility is completely lost even in the case of a substantial overlapping.

It is customary to install *C–N* and *C–S* systems on the two side circuits of a phantom group. The phantom group comprises four wires which are most closely associated electrically because they are employed not only to provide a telephone circuit on each pair of wires but a phantom telephone circuit each side of which is comprised of one pair of wires in parallel.

A typical arrangement of facilities afforded by one

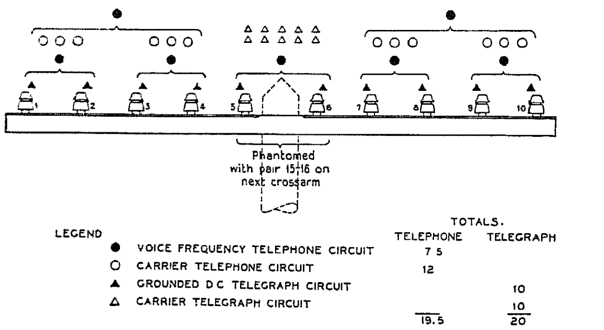

FIG. 16—ARRANGEMENT OF COMMUNICATION FACILITIES ON ONE CROSSARM

crossarm of the telephone line is illustrated by Fig. 16. It will be noted that this crossarm provides a total of twelve carrier telephone channels, five regular telephone circuits, two and one-half phantom circuits, thus making a total of 19½ telephone circuits. The telegraph facilities would total ten regular grounded d-c. telegraph circuits, one for each wire, and ten carrier telegraph channels on the pole pair, thus affording a total of 20 duplex telegraph channels. This is, therefore, an average of approximately four telephone channels and four telegraph channels per pair of wires, which is obviously a fairly efficient use of the copper wire.

Impedance. It is found desirable in connection with communication circuits in general to match carefully the impedances of the various circuit and apparatus components if for no other reason than to insure the best transmission by keeping the reflection losses at a minimum. In connection with carrier systems the matter of crosstalk constitutes an additional important reason for doing this. As noted above, the cross-talk situation is simplified by the standardization of frequency arrangements by which only far-end cross-talk is normally received. This not only reduces the level differences at which cross-talk takes place as explained, but it simplifies the transposition design problem because near-end cross-talk is normally greater in magnitude than the far-end cross-talk. However, if the line circuit is irregular, *i. e.*, if there are abrupt impedance differences in the circuit as it passes from point to point, which bring about wave reflections, these may result in near-end cross-talk being reflected and appearing as far-end cross-talk, thus adding to the true far-end cross-talk and making it more difficult to keep within desirable limits. For this reason every effort is made in the layout of the carrier lines to avoid such reflection effects. This makes it desirable to load even relatively short cables including office cables and wiring. The apparatus terminal impedances are also carefully designed so that their values simulate the characteristic impedance of the line circuits over which the systems are operated.

Over-all Line Circuit. A situation sometimes occurs in a long carrier system where the line is made up of sections in which the wire pairs occupy different pin positions in each section, and the voice circuit on the pair in which the carrier system operates is terminated at different points or perhaps joins other lines. The use of line filter sets at the intermediate points makes this arrangement possible. Special transfer line filter sets have also been designed where it is desired to transfer the carrier currents from one pair of wires to another without affecting the destination of the voice circuits and with a minimum impedance irregularity for either circuit. These line filters are sometimes mounted on poles so that this transfer may take place where lines join at an outside point and where office equipment cannot be installed. A circuit arrangement illustrating the use of the pole-mounted high-pass transfer filter set is shown in Fig. 17.

EQUIPMENT PROBLEMS AND TYPICAL INSTALLATIONS

The increasing use of carrier telephony as a substitute for line construction in providing toll facilities on

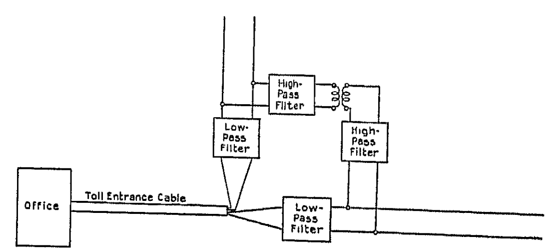

FIG. 17—SCHEMATIC OF HIGH-PASS TRANSFER LINE FILTER CIRCUIT

long circuits has, like the development of toll cables, resulted in further increasing the proportion of the plant investment represented by the equipment within the offices. It has likewise required that a greater part of the maintenance effort involved in taking care of a given number of facilities be devoted to the equipment. These factors have made the design and arrangement of the carrier equipment matters of considerable importance. Recent developments in these respects have, therefore, been directed toward obtaining a high degree of adaptability of the carrier equipment to practical use in the telephone plant. Economies in

design have also resulted which have been an important factor in extending the usefulness of the equipment.

The type C carrier telephone equipment is mounted on panels employing a uniform dimensional system in a manner similar to the other recent telephone developments. Arrangements have been devised so that in the future this mounting method will permit the desired close association between the carrier filters and other related apparatus in the lines in order to minimize high-frequency losses and impedance unbalances within the offices. Signaling arrangements flexibly adapted to present plant conditions have been provided.

The high frequencies and power levels used in carrier telephony, and the frequency conversion functions of the system are the principal electrical factors which affect the arrangement and amount of equipment involved. The high frequencies necessitate careful wiring, shielding, and location of certain units with respect to others to avoid undesirable inductive and impedance effects. The modulation and demodulation processes and the high energy levels required necessitate the use of numerous vacuum tubes, with the consequent need of suitable sources of power.

Typical System Equipments. As noted previously, a long carrier telephone system involves equipment at a number of intermediate repeater stations in addition to that at the terminals. Fig. 18 shows the principal equipment groups involved in a typical long carrier system. The particular system illustrated is one of those between Minneapolis and Chicago, with repeater stations at Waterloo and Dubuque, Iowa. The carrier repeater equipment is ordinarily additional to voice-frequency repeater apparatus used in the wire line as mentioned above and is connected so that the high-frequency currents for the carrier pass around the voice-frequency repeater. The wires concerned are employed also for d-c. telegraphy by the use of composite sets.

The principal groups of equipment involved in such a system include the carrier sending and receiving equipment and filters at the terminals, the repeater amplifiers and filters at the intermediate stations, and the line equipment and pilot channel equipment at all points. In addition, power supply equipment and testing equipment are required at all points, and voice-frequency and signaling apparatus at the terminals.

The total amount of equipment involved in a typical carrier telephone system shown in Fig. 18, exclusive of the power supply, includes altogether about 188 panels assembled on racks equivalent to 14 bays[7] and occupying a total floor space, including aisle space, of about 84 sq. ft. If the three channels which the system ordinarily provides were obtained by regular wire circuits, the office equipment might amount altogether to about 36 panels and 1.7 bays, occupying about 10 sq. ft. Thus, in a typical case, about eight times as much office equipment, other than that for the power supply, might be required to furnish a given number of facilities by carrier telephony, in comparison with that needed for the equivalent number of ordinary wire circuits.

Terminal Station Installations. The principal equipment groups comprising a terminal of a type C system are indicated in Fig. 19. A typical assembly showing a majority of these equipment groups is given in Fig. 20. This does not include the signaling equipment, the pilot channel, or the power equipment. A rear view of this same assembly is shown in Fig. 21.

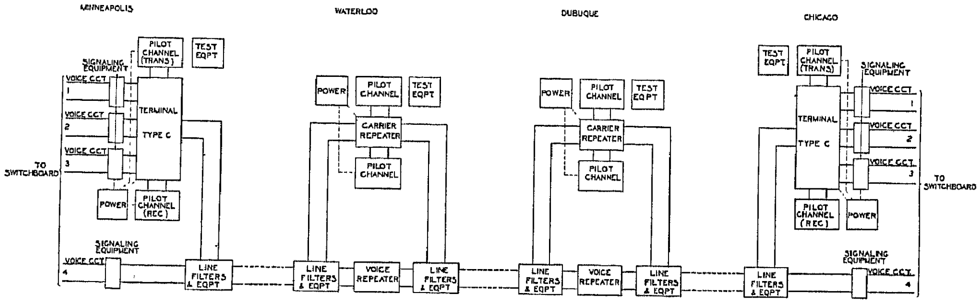

FIG. 18—ELEMENTARY DIAGRAM SHOWING PRINCIPAL EQUIPMENT GROUPS IN TYPICAL TYPE C CARRIER TELEPHONE SYSTEM

Returning to Fig. 20, the right-hand bay contains the apparatus comprising two channel terminals. The middle bay includes the third channel apparatus, and the terminal transmitting and receiving amplifiers and directional filters which are mounted in the upper portion. The box-like units on both bays are the band filters and directional filters. On the right-hand bay the upper of the panels with three vacuum tubes is the modulator-oscillator panel of one channel. Below it is the demodulator-oscillator panel of the same channel. Below the latter and in the center of the bay is the jack mounting strip which makes it possible to disconnect, or switch for testing purposes, the various units of the complete equipment. The demodulator-oscillator panel and modulator-oscillator panel, respectively, are the next two panels of the second channel. The terminal strips will be seen at the top of the bays. The

7. A bay consists of two channel or I-beam uprights, ordinarily about 11½ ft. high, and spaced so as to mount unit panels 19 in. wide and of varying height.

metal shields surrounding the vacuum tubes are useful for mechanical protection only. The testing and power distribution equipment is located in the left-hand bay.

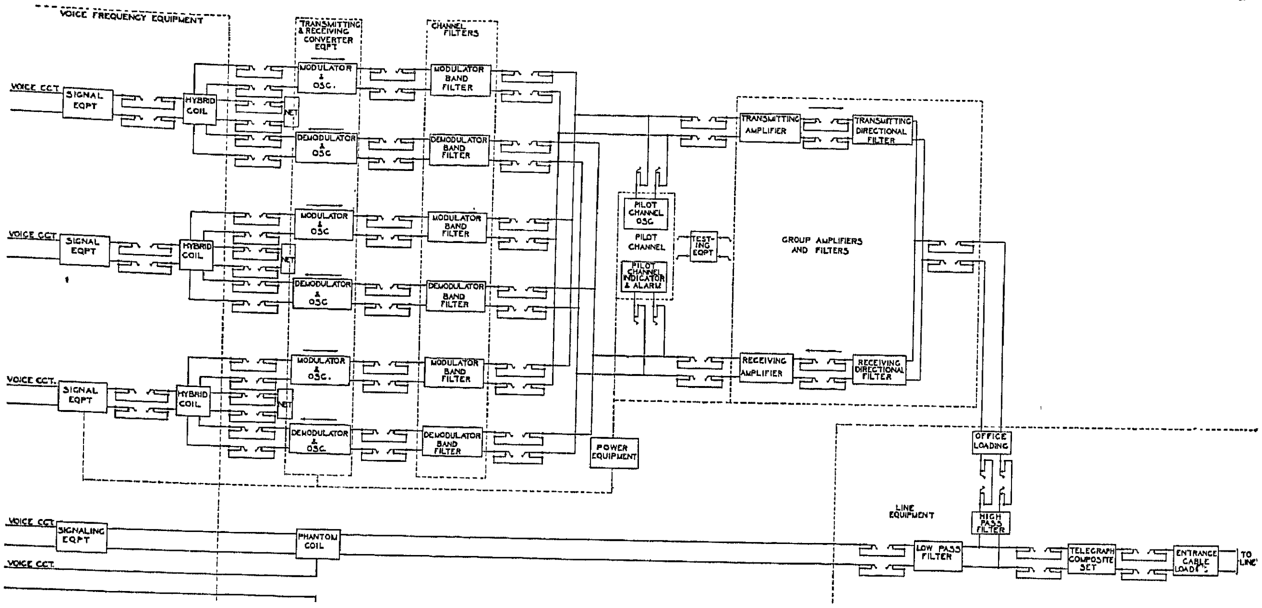

FIG. 19—SCHEMATIC SHOWING PRINCIPAL UNITS COMPRISING TYPE *C* TERMINAL EQUIPMENT

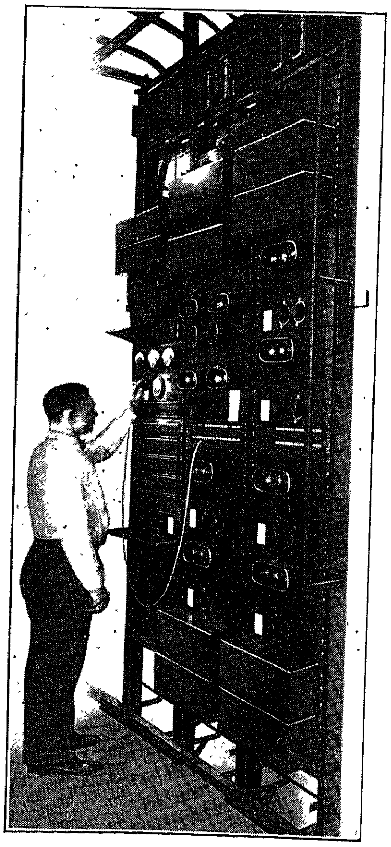

FIG. 20—TYPE *C* CARRIER TELEPHONE TERMINAL EQUIPMENT, TYPICAL ASSEMBLY OF SYSTEM. (FRONT)

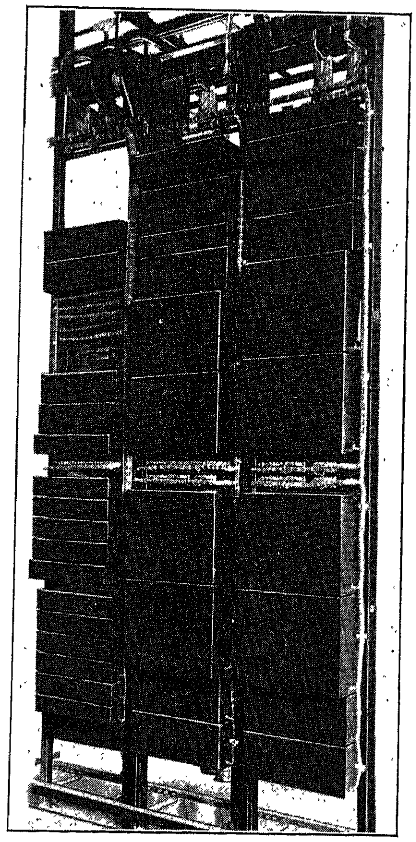

FIG. 21—TYPE *C* CARRIER TELEPHONE TERMINAL EQUIPMENT, TYPICAL ASSEMBLY OF SYSTEM. (REAR VIEW)

The pilot channel apparatus at the terminal station, which is employed in regulating the performance of the system to compensate for variations in the line equivalents, is assembled in a typical installation as shown in Fig. 22. This apparatus may be located adjacent to the carrier terminal apparatus. The upper panel is the indicator unit with the indicator meter shown in the upper center of the panel. The panel immediately below this is the alarm panel with its voltmeter relay.

On both of these panels the associated vacuum tubes are mounted in the rear. The lowest panel is the oscillator panel with its vacuum tube and frequency control.

Typical Repeater Station Installations. The equipment at each carrier repeater station consists mainly of the units indicated in Fig. 23. It is seen from this figure that the principal items are the line filter equipment, the amplifiers, the equalizers, the directional filters, and the jacks provided for testing and patching the equipment. Pilot channel equipment, power supply equipment, and testing equipment are also included. The amplifier equipment in each carrier repeater, other than the 15 TU auxiliary amplifier, is identical with the group amplifiers employed in each terminal station. The filters are also identical in type excepting that twice as many directional filters are required at each repeater station as at each terminal.

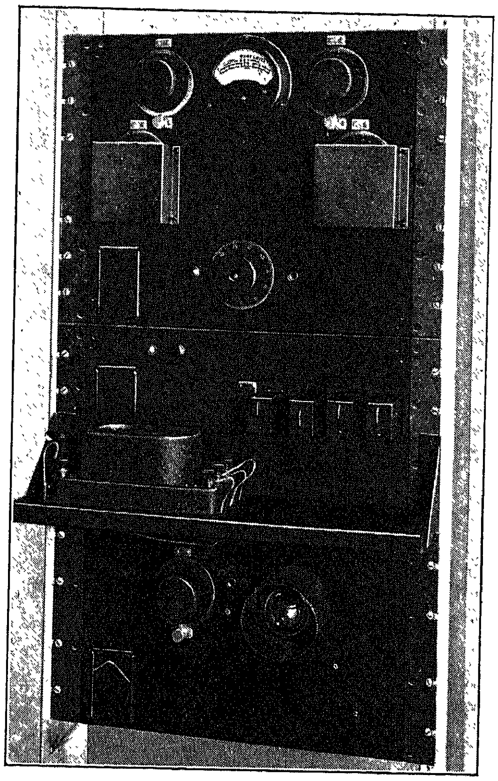

FIG. 22—TYPICAL ASSEMBLY OF PILOT CHANNEL EQUIPMENT IN TERMINAL INSTALLATION

A typical complete installation of two carrier repeaters with testing and battery supply circuits located in the bay at the left is shown in Fig. 24. The bottom panel on the left-hand bay is a reserve amplifier. Above this panel are the filament rheostats, telegraph instruments, jack panels, key panels for controlling the power supply, a panel containing a thermocouple and meter for testing, meters for reading currents and voltages, and finally the alarm relays. These last are operated by failure in the plate current in the amplifier tubes, thereby indicating when a tube burns out, or failure of either A or B battery supply.

Each repeater bay in this case, Fig. 24, contains an auxiliary amplifier to increase the gain in the high-frequency group. From top to bottom the panels are input filters, auxiliary filters, equalizers, auxiliary amplifier, two regular amplifiers separated by a jack panel, and output filters. The arrangement of filters and equalizers is chosen to minimize any tendency toward inductive feed-back effects between the output and input circuits of any one repeater as well as cross-talk between different repeaters on adjacent bays.

The pilot channel equipment at a carrier repeater station is similar to that employed at the terminal stations, excepting that the alarm and oscillator panels are not included. The alarm apparatus is omitted in this case, since it is not the practise to have the carrier repeater attendants readjust the carrier repeaters to take account of line changes, excepting when instructed to do so by the attendants at the terminal stations where the alarm apparatus is installed. The pilot channel equipment at each repeater station thus consists principally of an indicator panel associated with the transmission circuit in each direction, which is assembled with the other equipment as previously shown at the extreme right in Fig. 24.

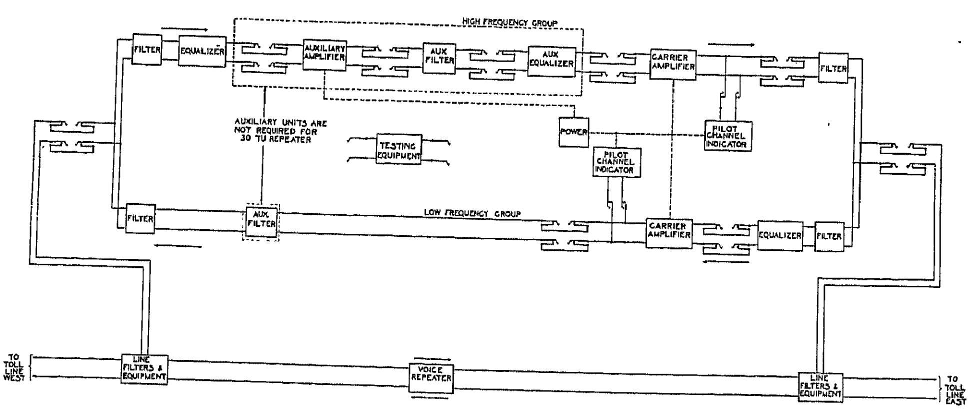

FIG. 23—SCHEMATIC SHOWING PRINCIPAL EQUIPMENT UNIT IN CARRIER REPEATER CIRCUIT

Line Equipment. Fig. 25 shows the principal line equipment units which are closely associated in effecting connection between the high-frequency circuit of the

carrier system and the voice-frequency line. This equipment consisting of the line filters, composite sets, and entrance and office load coils is mounted

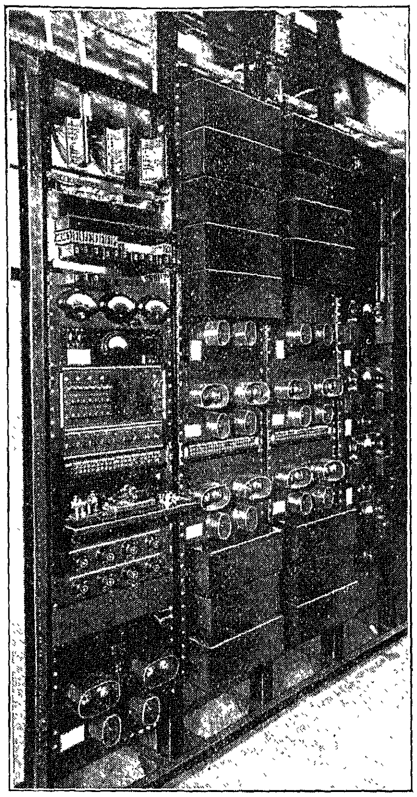

Fig. 24—Typical Installation of Carrier Telephone Repeater Equipment. (Front View)

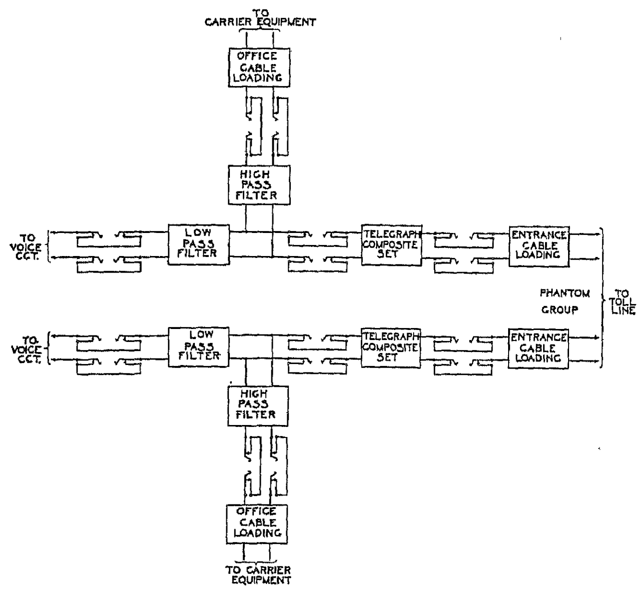

Fig. 25—Schematic Circuit showing Line Filter Equipment for Type *C* Carrier Telephone Terminal. (Phantom Group)

together in one assembly and located as near as practicable to the other carrier equipment. A method of assembly which is now under development is shown in Fig. 26. The bay shown contains the line equipment for two phantom groups.

This compact method of assembling and wiring the line equipment reduces the amount of office cabling required for the carrier and therefore reduces the possibility of inter-system cross-talk between carrier systems within the same office. The cross-talk requirements in an office may be more severe than on the pole lines because the level difference between circuits which operate on different pole lines terminating at the same office may be as much as 50 TU. As an aid in obtaining the required electrical separation all high-frequency wiring is reduced to a minimum by segregating and mounting together all line equipment associated with a single circuit. No high-frequency circuits appear at the toll testboard. The toll lines may be tested from the testboard by means of trunks between the testboard and the line equipment bays. All the carrier equipment is thoroughly shielded in such a manner that the separation between the equipment of any two systems is 120 to 135 TU.

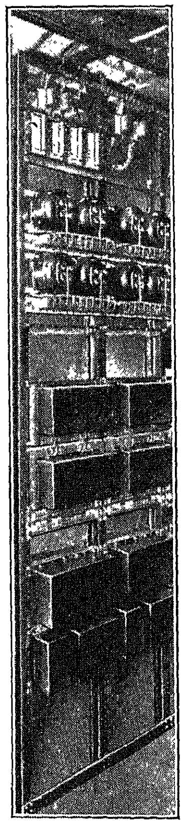

Fig. 26—Arrangement of Line Equipment in One Assembly for Type *C* Carrier Telephone. (Front View)

The carrier line equipment at a carrier repeater station is generally similar to that at the terminal stations, as previously shown in Fig. 26. At each repeater station, however, this equipment is provided in the lines in both directions. Two types of low-pass line filters are employed at the repeater station, one

adapted to circuits in which both carrier and voice-frequency repeaters are used and the other, which is less commonly used, for circuits employing only carrier repeaters and where the voice circuit continues through without a repeater.

Voice-Frequency and Signaling Equipment. The general function of the voice-frequency terminating equipment is to associate by means of a hybrid coil and

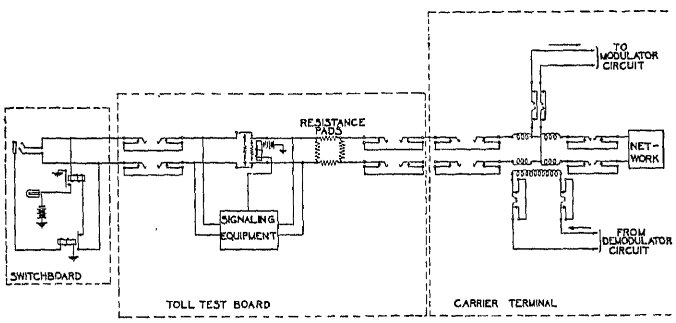

FIG. 27—SCHEMATIC OF VOICE-FREQUENCY CIRCUIT FOR TYPE *C* CARRIER TELEPHONE SYSTEM

network, the ordinary two-wire circuits in the telephone switchboard, including both talking and signaling functions, with the sending and receiving branches of each of the different carrier channels. The general arrangement of this equipment in the circuit is shown in further detail in Fig. 27. This includes the signaling equipment and makes provision for the connection of a balancing network.

The use of a two-wire termination for the carrier

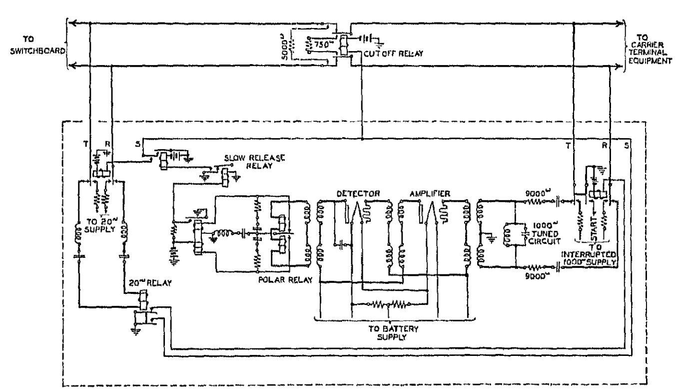

FIG. 28—SCHEMATIC OF 1000-CYCLE RINGING CIRCUIT

system is necessary because ordinary telephone circuits at the switchboards, such as trunks, subscribers' lines, etc., are of the two-wire type and the cord circuits for interconnecting these are of this type. Hence, such a termination of the carrier system makes it possible to connect it to other circuits with the same apparatus and in the same manner as with ordinary telephone circuits.

The signaling apparatus consists of a 1000-cycle ringer of the type which is employed on long voice-frequency lines. This is connected to the voice-frequency terminal of the carrier system in the same manner as to other voice circuits. The use of 1000-cycle signaling with the carrier has been desirable in place of the more simple low-frequency signaling apparatus used on shorter lines, since frequencies less than 200 cycles are not efficiently transmitted.

Fig. 28 shows a simplified diagram of this type of ringer. The transmitted signaling currents as impressed upon the carrier channel are of 1000-cycle frequency interrupted at a speed of 20 interruptions per second. This ringing current supply is obtained either from 1000-cycle generators or vacuum tube oscillators. Such currents, while in the voice-frequency range and thus capable of being transmitted readily, form a signal of sufficiently distinctive character to permit separation from ordinary voice currents. Thus, practical freedom from voice interference with the receiving apparatus is obtained, since this apparatus is designed to respond to very small currents of this character but to discriminate sharply against other currents.

Tests and Adjustments of Apparatus. For the purpose

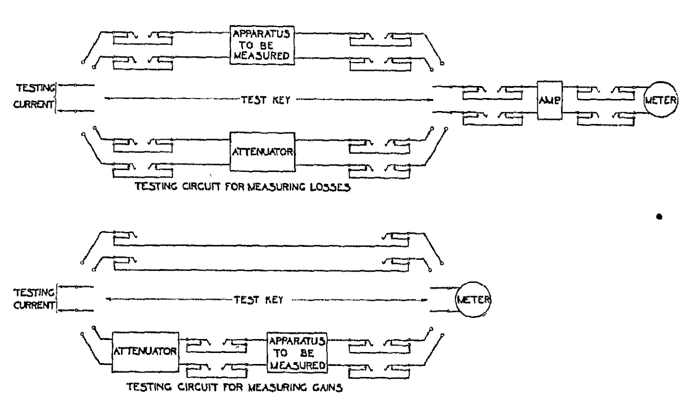

FIG. 29—SCHEMATIC OF TESTING CIRCUIT FOR TYPE *C* CARRIER TELEPHONE SYSTEM

of testing and "patching" (*i. e.*, interconnecting various equipment units in the carrier system), jacks are provided as previously shown in Fig. 19. The equipment which is employed for testing and adjusting the carrier apparatus provides means for measuring gains and losses at the various frequencies encountered and includes a supply of testing current at these frequencies. The general arrangement of the testing apparatus provided for measuring gains and losses is shown in Fig. 29. This is assembled with the other carrier equipment as previously shown in Fig. 20. It consists chiefly of means for switching a known loss in the testing circuit, an attenuator, and a calibrated thermocouple type measuring instrument for determining the value of the current transmitted through this apparatus. The 1000-cycle current is used for practically all testing of the terminal apparatus.

The testing equipment at a carrier repeater station is arranged in a manner similar to that at the terminal stations, as previously shown in a general way in Fig. 29. It requires in addition, however, a carrier-frequency

oscillator. Only high-frequency currents are transmitted through the carrier repeater, hence the 1000-cycle supply employed at the terminals where modulation and demodulation of these carrier currents occur, is not useful in testing the repeater equipment.

It is customary to make periodic tests of the equipment. On the longer circuits[8] each day the channels are "lined up" for the required over-all transmission equivalents. At less frequent intervals the vacuum tubes are checked for emission, the gains of the sending and receiving branches are measured, the carrier synchronism is checked, etc.

Vacuum Tubes. Two principal types of vacuum tubes are employed in this system. One of these is the so-called L tube. This tube has a filament circuit requiring a current of approximately 0.5 ampere with a voltage drop of 4.0. It has a μ of 6.5, and a normal plate current, when used as an amplifier with a B voltage of 130 and a C biasing potential of 8, of about 6.5 milliamperes.

For the output stage of the amplifier a higher capacity tube is employed. This is a so-called O tube having a μ of about 2.5, a filament current requirement of approximately one ampere at a voltage drop of 4.5. The normal plate current when used as an amplifier with a grid biasing potential of 22 and a plate potential of 130 volts is from 17 to 35 milliamperes.

In addition to the above the pilot channel uses a low-filament current tube. This tube has a μ of 8, a filament current of 0.060 ampere, and a filament voltage drop of 3 volts. The normal plate current when used as an amplifier with a grid biasing potential of 7 volts and a plate potential of 130 volts is approximately 0.003 ampere.

The tubes employ oxide coated filaments and have been designed to be especially long lived to meet daily 24-hour service requirements.

Power Supply. The power required for the carrier equipment is taken from the telephone office supply where this is adequate. Usually the 24-volt central office power plant is suitable for the purpose, and the 130-volt supply for the plate circuits of the tubes is taken from the same batteries provided for telephone repeaters if available. The carrier requirements, however, may amount to a substantial addition to the load on the power plant, particularly where several carrier systems are installed in a relatively small office.

The amount of power required for a typical carrier telephone system is substantially larger than the usual telephone power requirements for the same number of facilities. Each system terminal requires approximately 8 amperes at 24 volts and about 400 milliamperes at 130 volts. The power required for each carrier repeater amounts to about 4 amperes at 24 volts and 250 milliamperes at 130 volts. Thus the total power required for one three-channel system with two intermediate repeater stations would be in the neighborhood of 24 amperes at 24 volts and 1.3 amperes at 130 volts, amounting altogether to about 750 watts. This corresponds roughly to the amount of power consumed by about 80 telephone repeaters, so that the total power required for three such carrier systems would be about equal to that required for a cable repeater station having between 200 and 300 repeaters. Assuming 2 or 3 repeaters in a typical voice circuit, the carrier systems are seen to require over ten times as much power as voice circuits in providing the same facilities.

The best results are obtained with the carrier systems when very close regulation of this power supply is maintained. About $\pm$ 1 volt for the 24-volt supply and $\pm$ 5 volts for the 130-volt supply are desirable limits of variation. Means for obtaining such regulation are added as required to the existing power plant. In the larger offices this may consist of a duplicate battery with full-floating operation. In the smaller installations, a relay regulating circuit may be added which controls the filament current as the voltage varies from 20 to 28 volts. This consists of a sensitive voltmeter relay arranged with accessory relays to cut resistance in and out of the individual filament supply circuits as the voltage varies.

Design of Carrier Apparatus

Many will, no doubt, be interested in the further technical details of some of the more important units of the carrier system.

In the development of the apparatus considerable preliminary work was necessary to determine the circuit requirements imposed upon the individual units. For example, preliminary to the design of the filters, laboratory studies were made to find what interfering frequencies might be expected in a channel and what attenuation the different filters must offer at various points in the frequency range, in order that the system should provide speech of satisfactory quality and freedom from interference. As a result of such work, it was possible to make the requirements of the filters no more stringent than absolutely necessary, thus keeping the cost down to a minimum while insuring adequate performance. Preliminary studies were also made on the other parts of the system such as modulator, demodulator, oscillator, etc. In the descriptions which follow, no attempt has been made to describe this preliminary work, the discussion being limited to the requirements imposed, and the circuits devised to meet these requirements.

Modulator and Transmitting Oscillator. A circuit drawing of the modulator is shown in Fig. 30. It may be considered that the function of the modulator is to translate the voice frequencies along a frequency scale to some assigned location in the band of frequencies to be occupied by the carrier system. The carrier fre-

8. W. H. Harden, "Practises in Telephone Transmission Maintenance Work," *Bell System Tech. Jl.*, Vol. 4, Jan. 1925, p. 26-51.

quency controls the location of the shifted voice band or sideband, and the oscillator, which provides this frequency, is made an integral part of the modulator unit. The modulating process requires a circuit element having a non-linear response characteristic to produce the sideband from a combination of the carrier and voice frequencies. In this circuit the three-element vacuum tube is operated to give this required characteristic.

Since the carrier is not transmitted in the type *C* system, each modulator and demodulator becomes a complete and independent frequency changing unit. As previously noted the frequency stability of each oscillator must be sufficiently good so that the carriers of the corresponding modulator and demodulator units will differ but slightly in frequency so as not to affect unfavorably the speech which is transmitted. In this connection both naturalness of the received speech and intelligibility must be considered. In the type *C* system satisfactory results have been obtained by holding the difference between the carrier frequencies of any two associated units due to all causes to within about 20 cycles.

The usual causes of frequency variation are fluctua-

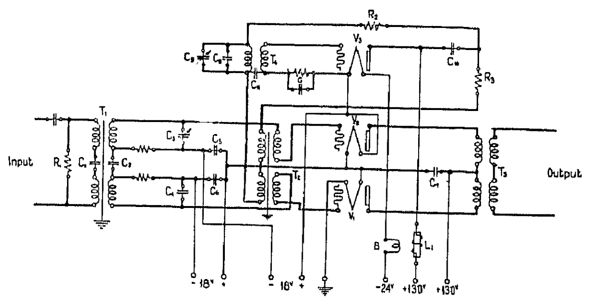

FIG. 30—SCHEMATIC OF MODULATOR CIRCUIT AND TRANSMITTING OSCILLATOR

tions in the A and B battery supply, and changes in temperature and humidity. Vacuum tubes have to be replaced periodically and differences in the tube characteristics may cause a slight variation in the frequency.

The type of oscillator circuit was chosen to furnish the greatest frequency stability with variations in power supply, particularly in the plate battery. Fluctuations in the filament current are reduced by the use of ballast resistors to a point where they do not appreciably affect the oscillator frequency.

In order to maintain stability with temperature and humidity changes, it was necessary to develop circuit elements, (primarily the inductance in the oscillating circuit) which were not greatly affected by these variables. As a result the oscillators vary less than 10 cycles per second at the highest carrier frequency with power variations within the limits of plant maintenance, and have a frequency temperature coefficient of approximately 0.002 per cent per deg. fahr. This corresponds to about one cycle per second per deg. fahr. in the highest frequency units used in the type *C* system. The temperature difference between offices containing terminal equipment seldom exceeds 20 deg. fahr.

An extreme change in frequency of 20 cycles per second may be encountered with different tubes. Maintenance experience has shown that it is usually unnecessary to check the synchronization of the modulator and demodulator carrier frequencies more often than once a week, unless tubes are replaced or some other unusual circuit change occurs.

The modulating tubes are placed in a push-pull arrangement, and the carrier voltage is applied to both grids in phase and the suppression of the carrier frequency secured by a differential connection of the output transformer windings. It is difficult to suppress completely the carrier and a limit is set upon the amount which can be allowed on the high-frequency line without causing interference between systems. This limit requires that the carrier flowing out from the modulator should not exceed approximately 500 microamperes. With varying conditions of power, the balance of the modulator cannot be maintained absolutely constant, so that to insure meeting this requirement under the worst conditions it is necessary to adjust the balance under normal conditions to a point where the carrier has been reduced to about 150 microamperes at the output of the modulator. The sideband current flowing at this place in the circuit is ordinarily of the order of 2000 microamperes. Adjustment of the carrier balance is made by changing the condenser across one-half of the input circuit, and by selecting tubes.

A further requirement imposed on the modulator unit is that of gain stability. In order to maintain sufficiently constant transmission over a circuit there must be a high degree of inherent stability in all those units whose variations are not included in the indications of the pilot channel. The modulator and demodulator are the only units in this category.

In the modulator and demodulator the principal factors tending to cause instability of gain are the variations in plate and filament battery where these occur and changes in the tubes during their life. A characteristic behavior of the modulator described below has been used to advantage in minimizing this instability. The gain of the modulator for varying values of the carrier voltage passes through a maximum near the point where the grids of the modulator tubes are driven to a positive potential, with respect to the filament. The output from the carrier oscillator will increase with increasing plate potential, and due to the above characteristic may be made to compensate somewhat for the tendency of the gain of the modulating tubes to increase. Fig. 31 shows the change in gain of the modulator circuit when the plate potential of either the oscillating or modulating tubes is changed independently. With these arrangements the total

variation in the modulator or demodulator gain, due to the fluctuations of power supply, does not usually exceed ± 0.25 TU. The possible variation due to tube differences is somewhat larger, approximately ± 0.7 TU. This is not serious since tubes are ordinarily replaced when a system is out of service, and the gain can be readjusted before the system is restored to operation.

Another requirement which the modulator must meet is one of transmission quality or equality in transmission gain at various frequencies in the voice band. The modulator should not limit the band of frequencies which is to be transmitted over the system. The characteristics of the transformers and the impedance in which the output of the modulator is terminated are the controlling factors in the quality of the modulator. A typical characteristic of modulator gain with frequency under ideal termination is shown in Fig. 32. In the type *C* system the effect of the band filter impedance is to cause a variation in this characteristic of approximately 5 *TU* at 2800 cycles.

The final requirement placed upon the modulator relates to the energy level which must be handled. It should not be possible to overload the modulator seriously with the amount of power produced by a subscriber's set at the transmitting toll testboard level. With a given modulator circuit, this requirement can be met by designing the input transformer with the proper turns ratio.

The following paragraphs give a more detailed description of the actual circuit which has been developed to meet the above requirements.

The voice-frequency circuit is through the hybrid coil to the terminals of the input transformer. The resistance placed across the input circuit is to improve

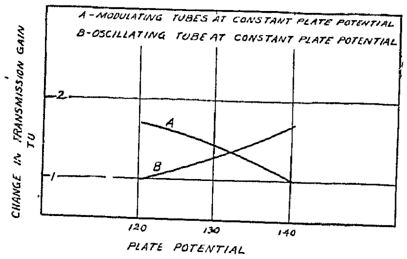

Fig. 31—Modulator Gain—Relation to Plate Potential

the impedance terminating this branch of the hybrid coil, and thus improve the terminal impedance looking into the hybrid coil from the voice-frequency line. The condenser *C*–1 is inserted in series with the primary winding of the transformer to improve the transmission characteristic of the circuit at low frequency. This condenser resonates with the inductance of the primary winding, increasing the voltage across the primary at low frequencies where the modulator input circuit tends to become less efficient. The two windings of the secondary side of the transformer are separated by bypass condenser *C*–2, as they are at different potentials from ground, due to the series connection of the filaments of the vacuum tubes. The variable condenser *C*–3 affords a means of balancing the carrier-frequency potentials. Condenser *C*–4 is one-half the maximum capacity of *C*–3 in order that carrier frequency unbalance in either side of the circuit may be compensated for to a sufficient degree by means of the one adjustable

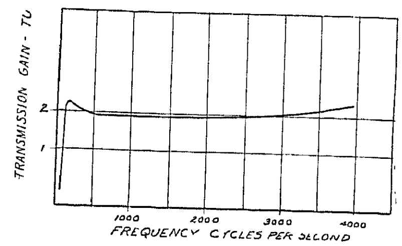

Fig. 32—Modulator Gain—Relation to Frequency

condenser *C*–3. The voltages, E_1 and E_2, provide the grid bias for the modulating tubes *V*–1 and *V*–2. The condensers *C*–5 and *C*–6 provide a low impedance path around the source of biasing potentials for the carrier frequency, and condenser *C*–7 in the plate circuit performs the same function with respect to the plate battery.

In the oscillator, the condensers *C*–8 and *C*–9 together with the inductance of one winding of the transformer *T*–4 form the oscillating circuit. *C*–9 is made adjustable to compensate for manufacturing variations in the inductance, and to provide in addition a certain flexibility in frequency adjustment. A grid bias for the oscillating tube is provided by the grid leak-condenser combination *G*. The plate battery is connected through the retardation coil *L*–1, which presents a high impedance to the carrier frequencies, and prevents their flowing through the plate battery. The carrier current in the plate circuit divides between two paths, one through *R*–2 the feed-back resistance to the grid circuit, and the other through *R*–3, the output resistance, and the transformer *T*–2 which impresses the carrier voltage on the grids of the modulating tubes. The filaments of the tubes in the modulator circuit are wired in series, and the current flow is regulated by a ballast resistor *B*.

Figs. 33 and 34 show the front and rear views of the modulator panel. The adjustable condensers which control the carrier frequency and the carrier balance are accessible from the front of the panel. In the rear view, the oscillator circuit occupies the left-hand side of the picture. The oscillating transformer is in the upper left-hand corner, with the oscillating condensers directly below it. The feed-back and output resistances are connected across the top of the panel. The oscillating tube is left of the three tubes, and the carrier input transformer is below it. The voice input transformer is

to the right of the carrier transformer, and the output transformer is located in the upper right-hand corner. A metal cover fits over the complete panel at the back to provide electrical shielding and mechanical protection. All outside connections to the panel are made through the terminal block in the lower right-hand corner. Wires supplying power, together with those which are at a low a-c. potential with respect to ground, are

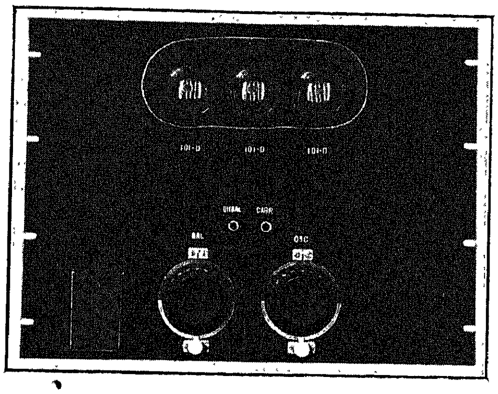

FIG. 33—ASSEMBLY OF MODULATOR PANEL. (FRONT VIEW)

run in a cable, while wires at a high a-c. potential are run directly from point to point in as short a path as possible in order to reduce losses resulting from the capacity of these wires to ground.

Demodulator and Receiving Oscillator. The circuit of

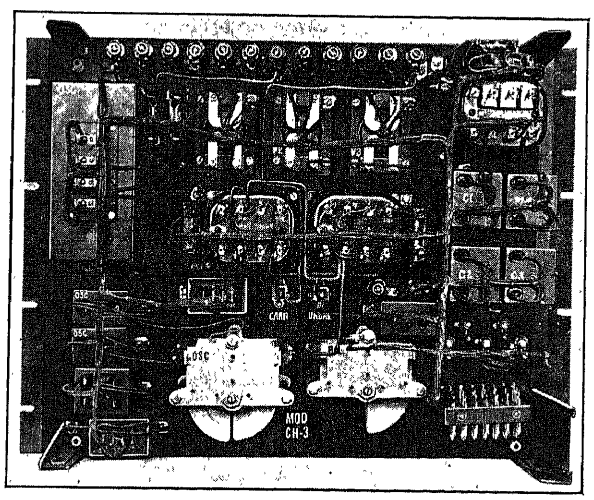

FIG. 34—ASSEMBLY OF MODULATOR PANEL. (REAR VIEW)

the demodulator shown in Fig. 35 is in many respects similar to that of the modulator. The function performed by the demodulator is also similar, being a translation from a high-frequency band to a lower instead of the reverse.

The oscillator which supplies the carrier to the demodulator is of the same type as the modulator oscillator, and has been discussed in connection with that circuit. No adjustable feature for balancing the carrier is required in the demodulator circuit. The carrier suppression needed in addition to the suppression inherent in the balanced circuit is provided by the low-pass filter at the output. If the carrier is not sufficiently suppressed, it will pass into the voice circuit or across the hybrid coil into the associated modulator, causing, in some channels, an objectionable beat tone.

The transmission stability of the demodulator is obtained by the same methods used in the modulator since the performance of the two circuits is similar, and the transmission quality requirement is essentially the same for both units. A typical demodulator character-

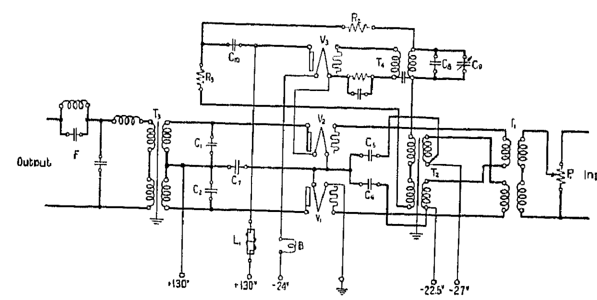

FIG. 35—SCHEMATIC OF DEMODULATOR CIRCUIT AND RECEIVING OSCILLATOR

istic is shown in Fig. 36. This characteristic at the higher frequencies is controlled by the low-pass filter.

One feature which is required with the demodulator, but not with the modulator, is a variable control of the transmission gain of the circuit. Due to the unequalized transmission of the line section adjacent to the terminal, or other differences in the channel equivalents, the three sideband currents normally arrive at a receiving terminal with unequal strength. A potentiometer controlling the gain of the demodulator permits of an equalization of the over-all losses on the three channels.

In the following detailed description of the demodu-

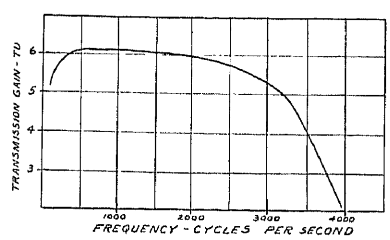

FIG. 36—DEMODULATOR CHARACTERISTIC—GAIN AND FREQUENCY

lator circuit, other minor differences between it and the modulator may be pointed out:

The sideband frequencies enter the demodulator, passing to the potentiometer P–1, which controls the amount of current to the input transformer T–1. The position of the carrier input transformer T–2 is somewhat different in the demodulator circuit as compared to the modulator circuit, due to the difference in the high-frequency characteristic of the T–1 transformers. In the modulator, this transformer must be designed primarily to transmit voice frequencies. It has a com-

paratively large capacity to ground which would reduce the effective carrier voltage on the tube grids if it were placed in the same circuit position as is the demodulator transformer. The function of most of the circuit elements is evident from the previous description of the modulator. The C–1 and C–2 condensers provide a low-impedance path for the carrier frequency. They are necessary here because the transformer T–3 designed for high efficiency at voice frequencies has considerable leakage inductance which would present a high

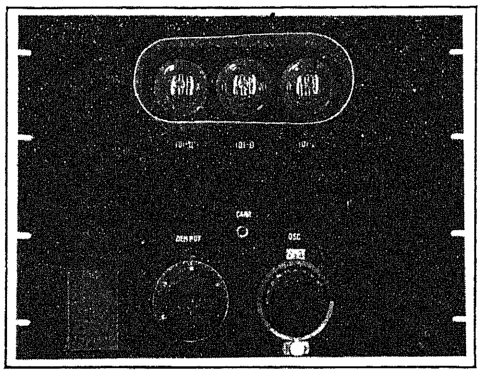

FIG. 37—ASSEMBLY OF DEMODULATOR PANEL. (FRONT VIEW)

impedance to the carrier in the plate circuit if the condensers were not provided. Of course, for the maximum gain, the impedance of this circuit should be a minimum at carrier and sideband frequencies. At the output, a low-pass filter structure F provides for the suppression of the unwanted products of demodulation.

A front view of the demodulator unit is shown in Fig. 37. The panel layout and general appearance is similar to that of the modulator. The two dials shown control the demodulator input and the oscillator frequency, respectively, as indicated in these figures.

Filters. The general function of a band filter is the selection of a band of frequencies, and the protection of

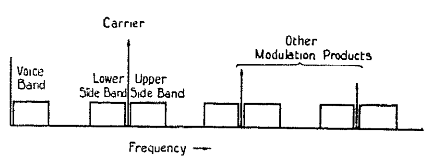

FIG. 38—FREQUENCY RANGE OF PRODUCTS OF MODULATION

this band from interfering frequencies located on either side. The filters determine what band width is transmitted, and thus to that extent, they control the quality of speech which may be obtained through the carrier circuit. The type C system transmits a band corresponding to approximately 200 to 2700 cycles per second in the voice range.

In considering the requirements imposed upon the band filters it is necessary to keep in mind[9] the fact that the modulator produces not only the particular sideband which is to be transmitted but also an unwanted sideband of the same volume as the wanted sideband and equal to it in width, located on the opposite side of the carrier frequency. In addition to these products of modulation there are produced other frequency bands, the important ones occupying sideband positions about the harmonics of the carrier frequency. See Fig. 38.

The first requirement on the band filters is imposed by the need of suppressing the unwanted sideband to prevent distortion when the carriers are out of synchronism. The tests mentioned above in connection with the oscillator frequency stability were made with but one sideband transmitted. If both sidebands are transmitted the carriers must be exactly in synchronism or a "wobble" due to the demodulation of both sidebands can be detected. As this carrier difference increases, one sideband must be suppressed by an increasing amount. For a carrier frequency difference of about 20 cycles, it is necessary to suppress the unwanted sideband about 40 TU, thus reducing it to about 1/100 of the strength of the wanted sideband in order to eliminate completely this type of distortion. This requirement can be met by providing the necessary attenuation in either the transmitting or the receiving band filter, or by making the sum of their attenuations equal to 40 TU.

In a multi-channel system in which the transmitted sidebands are close together, the suppression of the unwanted sideband is necessary for another reason. The unwanted sideband from one channel overlaps the wanted sideband of an adjacent channel and would be demodulated and appear as "cross talk" into this channel if it were not suppressed by the transmitting band filter. The suppression needed is determined by the amount of interference which can be tolerated from one channel to another. It has been found that to meet this requirement the transmitting band filter must suppress the unwanted sideband about 60 TU. The other modulation products mentioned above must also be reduced by the transmitting band filter to a value which will not cause interference in any channel into which they might pass. The discrimination requirement for these frequencies is less severe because the magnitude of these modulator products is not so great.

A particular termination is required at the end of the filter which is connected to the modulator. In order to get the maximum sideband power out of the modulator used, the impedance of the associated band filter, seen from the modulator, must be made low over the range of voice frequencies.

With the channels placed close together and coordination of different types of systems depending upon the channel locations, it is important that the band filters remain constant after manufacturing and that all filters of the same type be manufactured to meet close requirements. For proper coordination between sys-

9. R. V. L. Hartley, "Relation of Carrier and Side Bands in Radio Transmission," *Bell System Tech. Jl.*, Vol. 2, April 1923, pp. 90-112.

tems, it has been found desirable to keep all the channel bands within ± 125 cycles of an assigned location. In the higher frequency channels, this means that the filters must be manufactured to a frequency accuracy of the order of ½ of one per cent.

The attenuation requirements for the receiving band filter are somewhat different from those of the transmitting band filter. The purpose of the receiving band filter is the suppression of the frequencies of the adjacent channels as they are received over the line. In contrast to the transmitting filter, which must suppress the unwanted frequencies produced in its own channel, a filter with somewhat different characteristics could be used, therefore, for a receiving filter. While the requirements were determined separately for the receiving and transmitting filters, it was desirable in the interest of manufacturing economy to build both alike, setting requirements on the basis of a double purpose

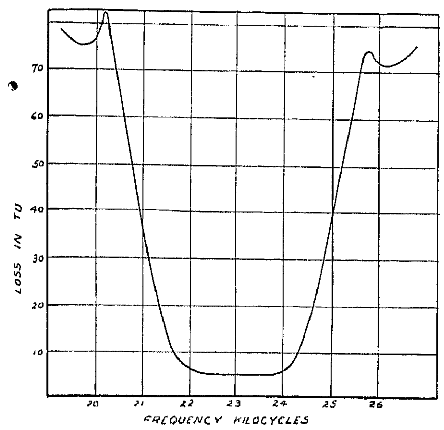

Fig. 39—Typical Band Filter Characteristic

filter. Thus, this filter had to provide attenuation at each frequency to meet the more severe of the requirements for either the transmitting or the receiving position. Fig. 39 shows the transmitting characteristic of a typical filter designed to meet the requirements outlined above.

As has been explained, the grouping of the channel bands in opposite directions requires the use of so-called directional filters at terminal and repeater points These filters occur in the circuit in pairs, each pair consisting of one high-pass and one low-pass filter. The cut-off point of the filters is determined by the type of system in use—*C–S* or *C–N* and its corresponding "grouping point." At repeater points, the filters are split for each direction in order to provide selectivity at both the output and input circuits of the amplifiers.

Considering the closed circuit through the two amplifiers and the four directional filters, the attenuation in this loop must be considerably greater than the sum of the gains of the two amplifiers at all frequencies. In the regions outside of the carrier frequencies, the margin between attenuation and gain is made about 10 TU. For frequencies in the carrier range, this margin must be still greater to prevent distortion which becomes objectionable when circulating currents of any size are allowed to exist. This "feed-back" effect will also affect the repeater input impedance, and because of the necessity for closely controlling this characteristic, the margin between gain and attenuation is not permitted to be less than 25 TU at any frequency used for transmission in either direction. The impedance of these filters on the line side must match the line impedance closely in order that no considerable reflection of the carrier currents can take place at this junction point.

As previously mentioned, due to modulation, the output of an amplifier contains other frequencies in addition to those which compose the input, so that cross-talk is to be expected between some of the channels. The amount of cross-talk which appears at the far end depends upon the ratio of the sideband currents to the interfering currents produced in the amplifier, the measurement being made at the repeater output. The near-end cross-talk, however, is dependent upon the level difference between the strong output of the one amplifier and the weak input to the other. Those frequencies which may give trouble in the channels at the near end enter the returning circuit at the amplifier input,—a point where the sideband level is very low. To put the near-end cross-talk on the same basis as the far-end, the output directional filter must introduce enough attenuation in its non-transmitting range, to make up this level difference. This attenuation is increased until the near-end cross-talk due to this cause is appreciably less than the far-end.

The output current of one amplifier may be 30 TU or more stronger than the input current to the amplifier for the opposite direction, and the directional filter at the input of this second amplifier must offer sufficient attenuation to the output currents of the first so that they will not contribute materially to its load.

Fig. 40 shows the selectivity characteristics of the two directional filters.

A pair of filters having important functions is the line filter set which, as has been noted, acts to separate the carrier currents from the regular speech currents on the common line circuit. It consists of a high-pass and a low-pass filter paralleled on the line side. Currents entering these terminals from the line circuit pass through the high-pass circuit, to the carrier apparatus, or through the low-pass circuit to the circuit terminal or repeater. The transmission characteristics of these filters are shown on Fig. 41. It will be noted that frequencies above approximately 3300 cycles are transmitted in the high-pass circuit, and frequencies below about 2800 cycles are transmitted through the low-pass circuit. In addition to those which are normally in use for carrier transmission, it is common to equip a few line circuits with line-filter sets. This makes it readily possible in case of an emergency, or for other reasons

to use the spare wires thus equipped for carrier transmission.

Non-linear effects may be produced in the coils and condensers in the circuit. The design of the filter parts

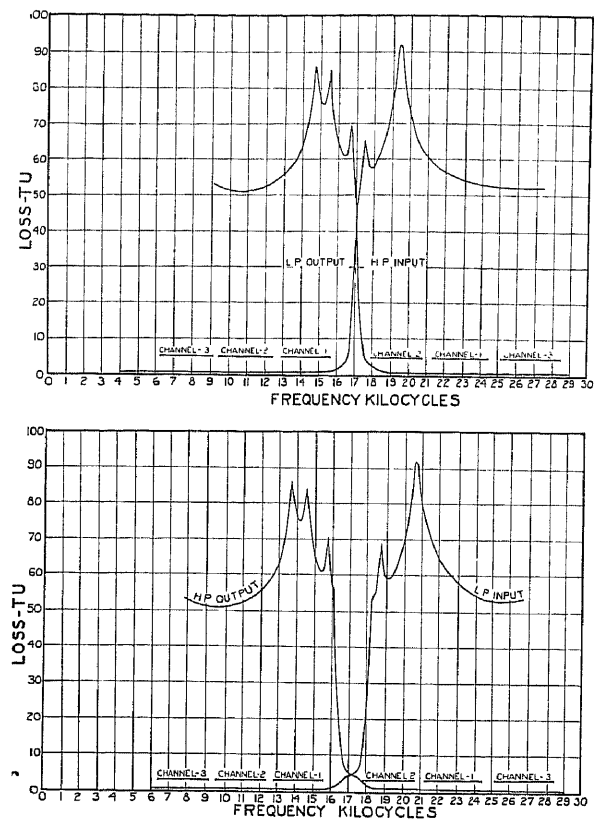

Fig. 40—Typical Directional Filter Characteristics

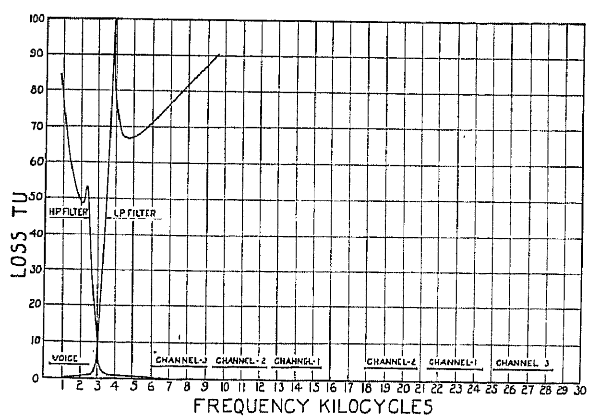

Fig. 41—Typical Line-Filter Characteristics

must be made so that these effects will be a minimum. This requires the use of non-magnetic cores in the coils, and also that the containers be of non-magnetic material. Condensers in magnetic containers must be located so that they will not lie in the field of the coils, and thus contribute to the modulation products. The modulation in the line filters, telegraph composite sets, and office and cable loading units must also be considered.

As already mentioned, care has to be exercised in the mounting of filters belonging to different systems in the same office, so that no cross-talk will be introduced from one system into another. A considerable level difference may exist between two filters of different systems, and it may be desired to mount these filters on adjacent bays. In order that the cross-talk between these two systems may be kept within desirable limits, the separation between the filters must correspond in attenuation loss in some instances to the order of 120 TU, or one part in a million. To meet this exacting requirement, the filters are totally incased in sealed copper boxes, the leads being brought out through small holes to terminal blocks.

Amplifiers. As previously mentioned, the amplifiers employed with the type *C* system at the terminals are identical with those used with the repeaters at intermediate stations. Therefore the following is applicable to both cases:

The number and size of tubes needed to deliver the

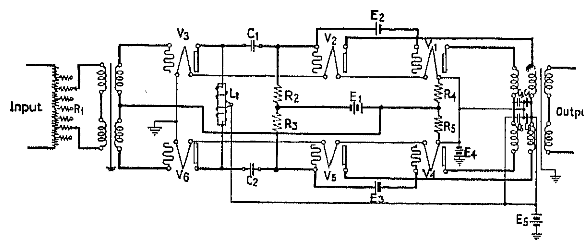

Fig. 42—Amplifier Circuit

necessary output level or power are largely controlled by interchannel cross-talk requirements. With the grouping frequency arrangement, the three bands which transmit in the same direction are amplified in a common circuit. In passing through the common amplifier, the different sideband frequencies must not react upon each other to produce other frequencies of sufficient magnitude to cause interference. For example, second harmonics of the lowest band frequencies lie within the range of the highest channel in the lower group. If these harmonics are permitted to become too great, troublesome noise will be present in the highest channel when speech currents flow in the lowest. In order that this interference or cross-talk may not become excessive, the tubes used in this amplifier must be made of ample power capacity. This example of interference caused by the second harmonic shows the desirability of using a push-pull amplifier in carrier repeaters because of its property of balancing out second order effects, which in a single-tube or unbalanced circuit are the largest of all the modulation products at the usual loads.

The currents from the three channels enter the carrier amplifier shown in Fig. 42. The circuit consists of two stages; the first stage of two tubes, the second of four of higher power rating. The gain is controlled in 2-TU steps by the adjustable potentiometer in the input. The gain frequency characteristics for different potentiometer settings are substantially flat within a small fraction of a TU over the range of any channel.

The amplifiers for the two directions are of slightly different design, each amplifier being arranged for a flat characteristic over its own group of frequencies. It has been stated that the load capacity of the amplifier is limited[10] by the modulation products which increase

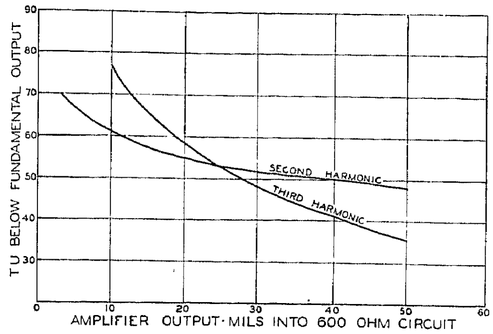

FIG. 43—AMOUNT OF SECOND AND THIRD HARMONICS AS FUNCTION OF CARRIER REPEATER OUTPUT

with the load. Fig. 43 shows the amount of second and third harmonics produced in a typical repeater with varying single-frequency output. By connecting the tube in push-pull instead of in parallel, the second harmonics have been reduced by about 15-20 TU.

When the alternating voltage applied to one grid is positive with respect to the filament, that on the other grid is negative. Since the even order products are proportional to an even power of the input voltage, these currents will flow through the high-side winding of the output transformer non-inductively producing no flux in the transformer, and hence no current in the low-side windings. To realize this ideal condition, the two currents flowing in the output transformer windings must be equal in amplitude, and 180 deg. out of phase. Since the plate current is a function of a number of tube constants, like amplitudes can be obtained in several ways. Tubes which will give the same harmonic current may therefore be selected; that is, tubes in which the net effect of the several factors is the same.

CONCLUSION

Use in Telephone Plant. The carrier systems are meeting successfully and economically the requirements of long distance telephone service. From what has already been written, however, it is evident that by its nature, the apparatus is complex and to a fair degree expensive, so that for the relatively short distances, it is cheaper to string additional wire. The exact distance beyond which it is more economical to employ carrier

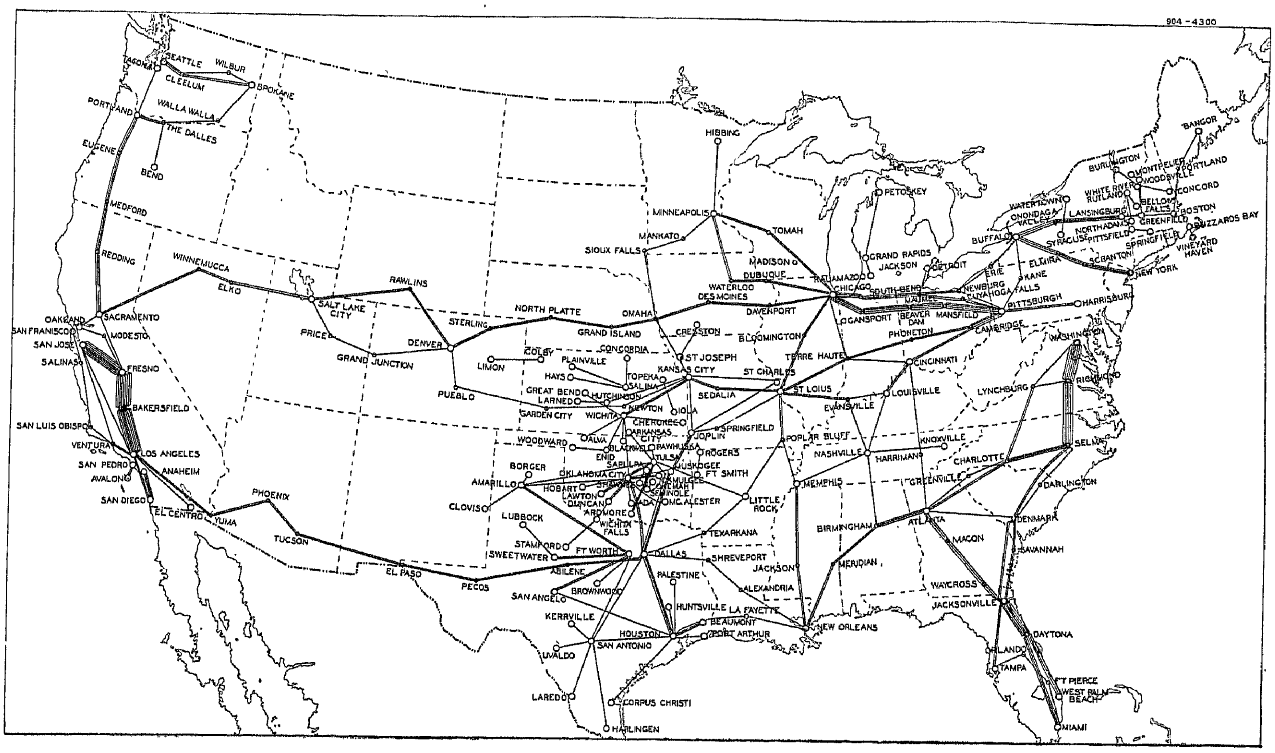

FIG. 44—MAP SHOWING CARRIER TELEPHONE SYSTEMS THROUGHOUT BELL SYSTEM

Other products of modulation, as well as the second and third harmonics, increase with the output and thus the power which can be taken from the amplifier under the operating conditions is limited, as these effects are likely to result in interchannel interference.

methods is obviously dependent upon the circumstances surrounding each particular case. Systems are operating for distances of 150 mi. and upwards.

Often where there are longer haul continuous physical circuits on the same line traffic growth requires additional circuits for the shorter distances. In such cases, it is not uncommon to break up the long-haul physical circuits into sections to satisfy the short-haul

10. F. C. Willis and L. E. Melhuish, "Load Carrying Capacity of Amplifiers," *Bell System Tech. Jl.*, Vol. 5, October, 1926, pp. 573-592.

circuit growth and to install a carrier system to meet the long-haul needs.

The growth of the use of carrier systems has already been pictured. How the systems are distributed over the lines of the Bell System is shown on Fig. 44. The heaviest density of use occurs in the middle and western sections and in general where the circuit demand and growth have not reached the large figures required to justify the installation of toll cables. The section west of the Mississippi, in particular, is a promising field for the application of carrier systems.

Future. While the type *C* system satisfies those circuit-growth demands for moderate- and long-haul, there has remained undeveloped a considerable field for carrier methods over the shorter distances where hitherto only wire stringing has been economical. Very recent developments have resulted in the trial and early field applications of a simple single-channel carrier telephone system designed particularly to meet these shorter-haul demands and thereby to secure the greatest practicable economy in providing facilities by carrier methods in the Bell System. Naturally it is finding its most extensive use in the sections of the telephone plant where the shorter circuits predominate. Because of the fact that the type *D* system development is only now being completed, it was thought desirable in the present paper to confine attention to the long-haul system (type *C*) and to defer the presentation of the detailed information on the short-haul development until a somewhat later date.

While since the beginning of their use, about ten years ago, considerable progress has been made in the development and application of these carrier systems, there is still much to be done in the matter of simplifications and further use of the high-frequency spectrum. Automatic pilot channel arrangements are being tested whereby manual maintenance costs can be reduced. Further developments are anticipated in the matter of transposition arrangements to permit an open-wire line to carry multi-channel long-haul carrier systems on most of its pairs. While the systems now in use in the field employ frequencies no higher than approximately 30,000 cycles, frequencies considerably higher than this can undoubtedly be economically employed.

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Discussion

C. S. Demarest: Certain points in connection with the development of the equipment referred to in the paper are perhaps of sufficient interest to warrant a few further remarks.

The amount of carrier telephone equipment in the plant of the Bell System is becoming quite large in those sections of the country in which open-wire circuits predominate. Approximately 150 systems are now in service on the longer circuits and the number is growing rapidly. In some installations this equipment, together with the repeaters and other associated apparatus of generally similar character, may comprise a considerable part of the total equipment other than the switchboards.

The satisfactory functioning of this equipment is vital to the service which the carrier system performs, since it is the basic means of providing the speech channels for additional facilities. Certain of the wiring and equipment arrangements affect both the performance of the systems and their practical application. Consequently, the details of these arrangements have required careful consideration.

Some of the problems have had to do with the matter of providing effective electrical separation between apparatus units and between wiring, while at the same time permitting assembly arrangements which would be desirable for plant use. The relatively high frequencies and large power-level differences occurring in the carrier systems, as compared with those encountered at voice frequencies, have necessitated some special provisions in this regard. Level differences as great as 50 TU, amounting to a power ratio of 100,000 to 1, may sometimes occur between apparatus units desired to be located closely together.

With ordinary telephone apparatus it has often been the practise to wire many individual apparatus units to terminals at a central distributing frame, in order that interconnections between units might be readily changed. With that part of the carrier apparatus involving high-frequency currents it has been desirable to modify this practise. The line equipment, for example, has been grouped together in one assembly and none of the individual apparatus units in this group has had wiring brought out to the distributing frame. This has reduced considerably the total length of the wiring per circuit within the central office, with consequent reduction in the losses and impedance variations which may be caused by this wiring. This has been a factor of some importance at carrier frequencies because of the relatively large capacitance per unit length of the office wiring as compared with the outside line wires.

Crosstalk between circuits which might occur in the wiring between apparatus units in this portion of the equipment is effectively prevented by using shielded cable. Special precautions are needed at the points in the high-frequency circuits where the conductors may be exposed electrically, even to a small extent. The connections between the lines wires and the group of apparatus comprising this line equipment are made at the top of the equipment bay by soldered connections to terminals arranged in rows less than ½ in. apart. Ordinarily, in voice-frequency circuits, the conductors in different phantom groups may be connected to adjacent rows of such terminals. In the case of the high-frequency carrier circuits, however, it has been found desirable to use only alternate rows of terminals, the intervening rows being strapped together and connected to ground so as to form a shield between the others. Somewhat similar precautions have been found desirable in the wiring to the jacks in the jack panel for the line equipment.

In order to permit mounting compactly the apparatus in the high-frequency portion of the circuit, it has been necessary to employ shielded units such as coils, etc. This has made it possible to locate such coils for separate circuits both on the front and back of the same panel. In the case of the filters, satisfactory shielding has been obtained only by assembling these in sealed copper cans, the ordinary removable can covers used in other telephone equipment being subject to sufficient leakage field at the junction point between cover and panel to make them unsuitable for filter use. With this type of shielding, the filters have been satisfactorily free both from crosstalk and from variations in characteristics due to the effects of surrounding apparatus of different types.

In caring for such requirements it has not only been necessary that the carrier telephone equipment should function satisfactorily of itself, but it has been essential that it should be capable of being correlated readily and flexibly with the circuits and equipments of various types in the plant. It has been advantageous to employ for the carrier equipment the panel-type mounting and assembly arrangements generally similar to those now used for much of the other toll equipment. This has not only effected the desired uniformity in design, but has provided features particularly adapted to the carrier equipment itself, as in the case of the line equipment just mentioned. It has also afforded the desirable features of economy in floor space and accessibility for maintenance purposes.

C. W. Green: One phase of this problem, the development of carrier systems, which I might amplify, is the question of crosstalk. The crosstalk between carrier systems on the same pole line is taken care of quite generally by transpositions. There is another problem, though, the crosstalk between the channels of a system, which requires attention in the development of apparatus for the carrier systems.

The currents of the three channels pass through a common amplifier and the characteristics of an amplifier are such that there are produced in the output, harmonics of the input frequencies, frequencies which are the sum and differences of the input frequencies and other combinations of the input frequencies. The design of the amplifier has to be such that those products of modulation are kept down very considerably in order that the crosstalk between channels will not be troublesome. This requires that, by care in the design and operation of the carrier amplifier, these products of modulation be maintained at lower levels than are usually necessary in voice-frequency amplifiers.

D. I. Cone: As shown on Fig. 44, much use has already been made of type C carrier telephone systems on the Pacific Coast and to points east now comprising 31 systems with 26,600 channel-miles of circuits. Extensive additional applications are now being engineered. These systems have made a splendid record in actual performance and providing for the large growth in long-distance telephone service pending the orderly development of the cable network. One of the two leads between San Francisco and Los Angeles is now carrying eight systems (24 channels) on two crossarms for a distance of 250 mi. This unusual density of concentration was secured in this case without sacrifice of the high quality and freedom from inter-system crosstalk.

Superimposed High-Frequency Currents for Circuit-Breaker Control

BY LEON R. LUDWIG[1]

Associate, A. I. E. E.

Synopsis.—*On railway or polyphase power systems having a multiplicity of parallel lines, there are unique possibilities in superimposing on the lines a frequency of the magnitude of 500 cycles, (together with the consequent apparatus), to gain selective protection under all fault conditions. The principle suggested is to measure the impedance of the power system with 500-cycle current and high-frequency relays, so placed that under abnormal conditions the impedance of a faulty line, as measured by the relays protecting that line only, is sufficiently low to cause circuit breaker operation.*

The advantages of such a protective system would be:

1. Perfect selectivity between parallel power lines, such that a faulty line may be isolated without disturbing other lines.

2. Instantaneous operation.

3. Simultaneous operation of protective breakers at the two ends of a faulty line.

4. Protection of the line against short circuits or faults, but the avoidance of breaker operation on heavy overloads when the current rush may be greater than at short circuit.

5. A measure of the continuance of a fault, permitting automatic reclosing of circuit-breakers.

This super-frequency control system brings to light a number of refreshing conceptions, and while it is not completely developed at this time, sufficient experimental work has been done to warrant presenting the results as a matter of technical interest.

THE CIRCUIT-BREAKER CONTROL PROBLEM

ANY relay or other type of apparatus called on to control circuit-breakers automatically, must meet an increasing number of rigorous qualifications. In addition to causing the breaker to operate if excessive currents arise in the system to which it is applied, there is a number of other requirements which are essential, or desirable, all or some of which must be fulfilled, depending on the system.

First, the system to be protected may consist of parallel feeders, any of which is liable to a fault. Should one of the parallel feeders become faulty at any point, it is essential that this feeder be disconnected from the system by opening circuit-breakers at both of its terminals, but parallel feeders should remain undisturbed. This desirability of perfect selectivity between parallel conductors may, if the fault occurs near one terminal, tax the ordinary relay beyond its limit of differentiation.

An increasingly important requisite is the high speed of both relay and circuit-breaker operation. On power systems, the ability of protective apparatus to isolate a fault rapidly is an important asset in maintaining stability. The dynamic stability may be greatly increased if the time required to remove a fault is somewhat less than that required for synchronous machinery to shift its phase angle appreciably. In case of nearby parallel telephone lines, telephone interference may dictate rapid isolation.

On many systems having a widely divergent load demand, heavy-load currents may exceed short-circuit currents if the short circuit occurs with the minimum of generating capacity connected to the line. The control equipment must act to isolate the short circuit, but should not open the loaded line, a condition which precludes the use of plain overload relays.

There are other desirable features of relaying systems, three of which may be mentioned. Circuit breakers are frequently tripped to temporary faults, in which case, if the relay could determine the nature of the fault, the breaker might be again closed and normal conditions restored without the need of an operator. Automatic reclosing would be particularly advantageous if, with the circuit-breaker open, the relay could determine whether or not it might safely be reclosed. From the standpoint of telephone interference, a further requirement is the simultaneous operation of the circuit-breakers which are to open, or the avoidance of "cascade" operation. The third feature is a relay system which could be set and tested for proper operation without the necessity of actually placing a short circuit on the power system.

A combination of the above problems has so strained the usual concepts of relay procedure that an entirely new basis of circuit-breaker control is desirable and may be found in the application of a superimposed high-frequency current system. The purpose of the new system is therefore to extend the limitations naturally imposed by the use of normal frequency relays.

DESCRIPTION OF THE SYSTEM

The 500-cycle system consists essentially of a source of high-frequency power, a means for introducing it into the lines to be protected, means for obtaining selectivity in case of parallel lines, and the circuit breaker operating relays. The system is equally applicable to a single-phase railway system or a polyphase power system. An application to a single-phase system may be described first for simplicity. In Fig. 1 is shown a grounded single-phase system, which may be a railway network. There are two parallel contact lines supplied with power from transformers located in three substations. A circuit breaker is placed in each end of each contact line.

The 500-cycle current is introduced into the system by a connection from the generator or power source to the ground side of the main transformer. The other

1. Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.

terminal of the power source, which is usually a small high-frequency synchronous generator, is connected to the ground. A high-frequency power source is necessary at each point in the network where power current of normal frequency is supplied. To prevent the high-frequency generator from being short-circuited by this connection, a resonant device consisting of a condenser in parallel with an inductance is placed in the main power circuit between the point of connection of the generator and ground. The condenser and inductance are each designed to have the same reactance at the

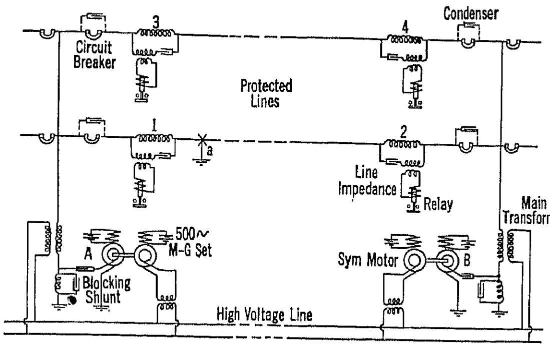


Fig. 1—Protective System Applied to a Single-Phase Network

high frequency, and therefore if their resistance is low, their combined impedance will be very high. Currents of normal frequency pass easily through the inductance, which has in itself a very small impedance. The parallel circuit may be referred to as a "blocking shunt."

In order to gain selectivity between parallel lines, a device similar to the blocking shunt, though very much smaller, is placed in each end of each line. Its function is purely as a line-impedance at the high frequency, with the advantage that considerable impedance may be obtained by the use of a very small reactor in this way. A high-frequency current will circulate in the parallel line-impedance which is proportional to the high-frequency current in the line. The relay itself may therefore be connected to a current transformer placed in the condenser branch of the line-impedance. The condenser will carry very little of the power current, which means that the relay will function solely on high-frequency current proportional to that in the line.

Description of Operation

Normally, with no fault or load on the contact lines, the generated voltages of the high-frequency machines are equal and opposed. These machines will synchronize and there will be no appreciable current flowing in the contact lines. To further aid in keeping the voltages opposed, the generators are driven by normal-frequency synchronous motors, which will maintain an almost constant phase position.

If a ground occurs at (a) on one of the lines, high-frequency current will flow from the generator through the main transformer to the contact line, then to ground through the fault, and return. An appreciable current will therefore circulate in the resonant line impedance (1) and (2), sufficient in magnitude to trip the corresponding relay. Some current will also flow from the generator *B* through the line (3-4), but this current will be less in magnitude because it must pass through three line-impedances instead of one as in the former case. Then the current in the parallel line will not be sufficient to trip the relays at (3) and (4). For similar reasons, the remaining relays in the adjacent lines will not be tripped.

In case some form of load is connected to one of the contact lines—a locomotive for example—high-frequency current will flow to ground through the load, but will not be sufficiently great to trip any of the relays because of the load impedance. It is fundamental that the high-frequency current always provides a means of measuring impedance regardless of the network. Normal speeds of rotating machinery are so much below the high-frequency synchronous speed that practically no counter-voltage is generated at this high frequency. It is also usually the case that the blocked impedance of the load is high in comparison with line impedances, which means that there is a good margin of differentiation between heavy loads and short circuits. In brief, the high-frequency system may be looked upon as a network equivalent to that of the

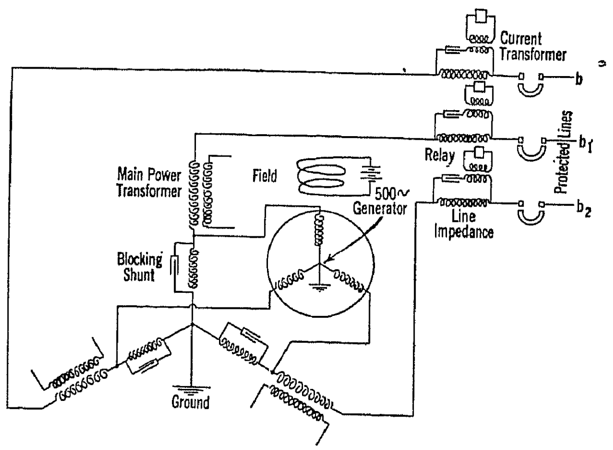


Fig. 2—Protective System Applied to a Three-Phase Network

normal frequency except that all normal frequency rotating apparatus may be considered as blocked.

Polyphase Application

The means of using this apparatus on a polyphase system is shown in Fig. 2. The high-frequency generators must now be polyphase. Their current may be introduced in the neutral side of the main transformer winding, three of the blocking shunts per power source being required. It is assumed that the main transformers are connected in star with a grounded neutral. Otherwise, the method of connection will be given later. If there are parallel lines, line impedances must be used as before. The principle of operation is

the same; namely, that the high frequency is introduced and the line impedances are so placed that the impedance measured by a given relay is the correct impedance to cause that relay to trip, provided there is a fault on the line it protects. By tracing the path of current in the diagram, it can be seen that a short circuit between lines $(b_1 - b)$ will cause a relay-actuating current to flow.

Discussion of Special Problems

The system depends so largely for its successful operation upon the parallel resonant circuits that special mention of their properties will be made. If the condenser and reactance are resonant at the chosen high frequency—500 cycles for example,—then at 25 cycles the reactor will have one-twentieth of its high-frequency reactance. The condensive reactance will be increased twenty times at normal frequency, or 1/400 of the load current will pass through the condenser. The reactor must be designed, therefore, to carry the

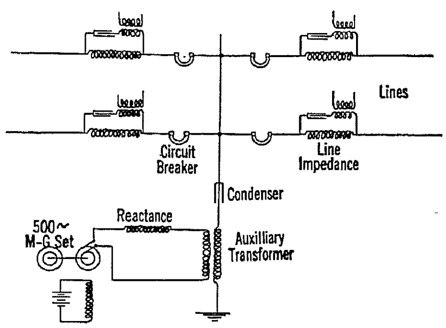


Fig. 3—Special Method of Introducing Auxiliary Current Into a Line

load current. The impedance of the parallel device is very nearly $Z = \frac{x^2}{r}$ in which x is the reactance of either the condenser or reactor and r is the resistance of both. Practically, if x is increased beyond a certain point, r must be increased directly with it, or the impedance will vary as the first power of the reactance.

It is easy to obtain an impedance of a few hundred ohms, which is sufficient for the blocking shunts, with a comparatively small reactor and a single condenser unit. The line impedances require about 40 ohms, which is very easily obtained.

In certain networks the blocking shunts may serve another function than previously explained. It may be desirable to subdivide a complicated system into a number of simple high-frequency systems in order to measure the impedance of the simplified systems. The ability to do this by inserting the blocking shunts at predetermined division points, is very important because the most involved network may be resolved into a number of small networks for the purpose of facilitating high-frequency relay protection.

There is a special problem also in getting the proper connection of the high-frequency power to the protected lines. To avoid insulation to ground of the high-frequency apparatus the connection in Figs. 1 and 2 is made on the low side of the transformer. This method is feasible because the reactance of a large power transformer is low. The transformer reactance is, in fact, helpful because the high-frequency system should be laid out in such a way that short circuits on the protected lines are loads, not short circuits, upon the protective system. In some cases, however, there are circuit breakers to be controlled at points where no transformers are used. In this event, the procedure is to make the connection as in Fig. 3. The condenser in the specially provided tap has sufficient reactance to prevent the normal-frequency currents from flowing to ground. The transformer reactance, plus the additional reactance inserted in the generator circuit, is sufficient to overcome the high-frequency reactance of the condenser, and the superimposed current may easily enter the lines. The transformer in the figure is very small, having the same rating as the high-frequency generator.

In three-phase systems, the transformers may be delta-connected, or there may be no ground. A high-frequency ground may be provided by connecting the neutral to ground by means of a condenser. In case of the delta-connected transformers, the method of introducing the current shown in Fig. 3 may be used in three-phase form.

There are a few special considerations in the use of 500-cycle synchronous machines and the steps taken to keep them in phase opposition. The power required from these machines is that necessary to operate the relays and supply the high-frequency line loss. Two kilowatts are ample for a large system. Machines of this frequency synchronize quite as well as those of lower frequency, provided too much reactance is not present between the two. The length of a section of line to be protected is often sufficiently short so that the reactance between generators will not cause synchronizing difficulty. In case it does, however, the high-frequency voltage may be stepped up by means of a transformer in order to decrease the effective reactance. Normally the high-frequency potential need not be more than 250 volts, though it may run much higher on long lines.

Fig. 1 shows the generators driven by synchronous motors connected to the main power feeder. If this connection is made, there are two closed systems interconnecting the motor-generator sets at two frequencies. If there is a difference in the phase angles of the voltages of power frequency at the two motor-generator sets, there must be flexibility in the inter-connection. This flexibility should occur in the power-frequency side of the motor-generator sets and may be obtained by the use of a flexible coupling between the two machines of the set, or by placing reactance in series with the synchronous driving motors. Either of these

devices will aid in keeping the high-frequency voltage closely in phase. A synchronous driving motor has been selected because it permits the auxiliary generators to supply power at constant speed and frequency. The constant frequency is essential to prevent the parallel shunts and line impedance from departing from resonance.

The final component of the system needing special discussion is the relay. In Fig. 4, a 500-cycle mechanical relay is shown which has two elements connected in series. The function of the relay is to trip if a rapidly rising current of sufficient value is passed through it. This limitation of a rapidly rising current is obtained by the use of the second element. The dashpot shown in the figure will slow down the second element whose function is to tighten the spring restraining the tripping element such that if the current rises slowly a very high value will be necessary to trip the main element. The purpose of using such a relay is to prevent synchronizing currents between the generators, which currents must rise slowly on account of the mechanical inertia of the generators, from causing the relay to operate. A second purpose is to "pre-set" the tripping element as the load upon a section of protected line varies or as the generating capacity connected to the section of line varies.

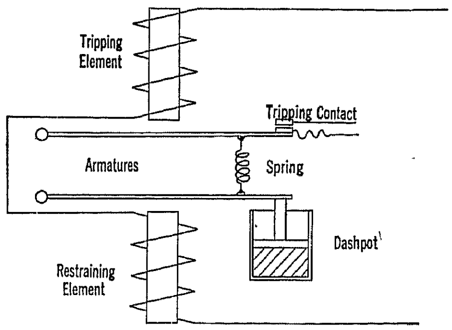


FIG. 4—HIGH-FREQUENCY PRE-SETTING RELAY-SCHEMATIC DIAGRAM

A vacuum tube relay may be substituted very nicely for the mechanical relay, with the advantage of increased speed. A relay used for this purpose is shown in Fig. 5. It is a neon-filled tube with a double purpose; first, to break down at a predetermined voltage in the manner of the well-known glow tube, and second, to pass a high circuit breaker tripping current as a mercury arc rectifier. The two lower electrodes consist of mercury pools, and the upper electrode is a hollow metal cone. If the voltage between the upper electrode and the smaller lower one reaches a given value, a glow discharge occurs between the two, which causes a mercury arc to be formed between the upper and main lower electrodes. The tube is a further development by D. D. Knowles of the earlier Knowles' Grid-Glow Tube. It is capable of momentarily passing a tripping current of a few hundred amperes. The entire action is very rapid.

The connections using the tube relay are shown in Fig. 6. The device at the left takes the place of the pre-setting element on the mechanical relay. The entire relay apparatus in this case operates from voltage, actually the voltage of the current transformer in the line impedance circuit with a high impedance across its secondary. The pre-setting device consists of a one-to-one transformer whose exciting current is

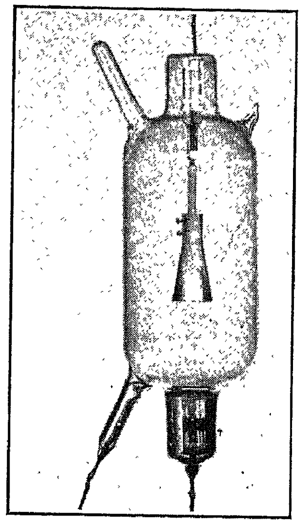


FIG. 5—HIGH-FREQUENCY VACUUM TUBE RELAY

obtained from a resonant circuit. The transformer connections are made in such a manner that the secondary voltage, under steady state, opposes the primary voltage and leaves zero voltage across the tube. During the transient, however, as a voltage is applied, the rise of the primary exciting current is very slow, and initially there is a voltage across the tube. Then the tube will operate if the voltage is rapidly increased to the breakdown point, but will not function with a slowly rising voltage.

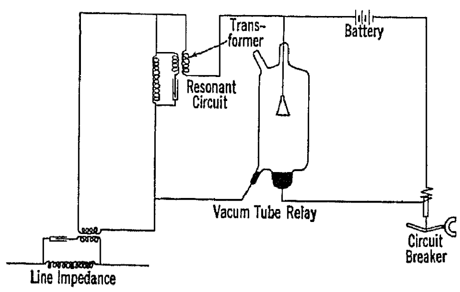


FIG. 6—CIRCUIT USING THE VACUUM TUBE RELAY

Mention has been made of the feature of automatic reclosing of circuit-breakers. If the circuit breakers in Fig. 1 are shunted with a condenser which will pass the high-frequency current only, with the circuit-breaker open, the high-frequency current will retain the relays in their operative position as long as the fault remains on the line. However, at any time that the

fault is removed, the relays will return to normal and permit the breaker to reclose. Such a connection would be advantageous if the protected system is liable to faults of short duration.

Results of Experimental Investigation

For the purpose of making an oscillographic study of the system, it was applied experimentally to an 11,000-volt test track contact line at the Westinghouse Works in East Pittsburgh. The experimental circuit is shown in Fig. 7. Four lines were used, and they were joined in pairs at one end in order to give two parallel lines with both terminals at the same location, the latter being for ease in testing. The lines were fed by 11,000-volt single-phase transformer banks at both ends. Two blocking shunts were placed in the grounded side of the transformers and a line-impedance was placed in each line. Arrangements were made so that a short circuit could be applied to either end of either line. Vacuum-tube relays were placed on lines 1 and 4, and were connected to trip the circuit breakers *A* and *B*. The

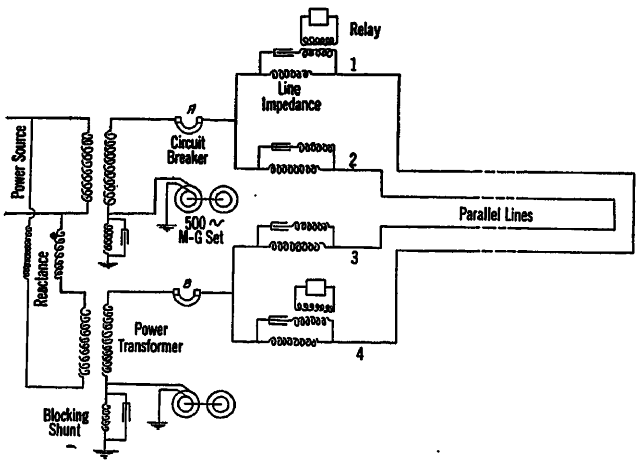


Fig. 7—Circuit of Experimental Test

apparatus was set up mainly to demonstrate speed of relay action and selectivity.

From the previous description it is obvious that a short circuit at the end of the line is the most severe condition to meet. Selectivity is most difficult to obtain, and there is the greatest danger of the auxiliary generators running out of synchronism with the short circuit at this point.

The first tests were made with high-frequency current alone applied to the line. The relays may be properly set, therefore, without the application of power current, by placing short circuits at the various indicated points and adjusting the tube voltage so that it trips with a fault on line (1-4) but not with a fault on line (2-3). The tube relay circuit was that shown in Fig. 6. In making these first tests the low-tension side of the power transformers must be short-circuited.

The frequency used was 525 cycles obtained from a small rotating machine, at 250 volts. Standard oil-filled condensers were used in the impedance circuits; the current transformers also were standard. The oscillogram in Fig. 8 was taken with a short circuit at the end of line 1. The lower element recorded the high-frequency current flowing from line to ground. The other two elements are a record of the current in the upper electrodes of the tube relays at 1 and 4. It will be recalled that both the circuit breaker tripping current (d-c.) and the high-frequency breakdown current flow in this electrode. The film, then, shows the high-frequency current superimposed upon the direct current. The d-c. component is similar to that which flows in the tripping coil of a circuit breaker, and the shape of the curve is familiar. The high-frequency component will be seen to gain in magnitude. The first tube operated two and one-half cycles, high frequency, after the short circuit occurred, and the second tube, two cycles later.

A potential of 11,000 volts was then applied to the lines at a frequency of 25 cycles. A short circuit was placed on line (1-4) at 4, and Fig. 9 is a record of the short-circuit current in line (1-4) at 1 and of the current in the tube relay at the same point. There is no discernible time lag from the instant at which the fault was applied to the instant at which the relay furnished tripping current to the breaker. The actual time, obtained from other tests, is about 1/2000 of a second. This time is independent of the point on the power frequency voltage wave at which the fault is applied, but will vary slightly, depending on the point of fault application on the high-frequency wave. The maximum time is about one-quarter cycle, high frequency. Fig. 10 shows the breakdown voltage of the two tubes, from which it will be seen that the voltage reaches its maximum in one-quarter cycle. The striking feature of the films is that it is not necessary for the relay to wait until the power current becomes excessive before operating. It will be noticed that the speed is much greater with power current on the line, because of the initial charge of the condensers. Fig. 11 shows the short circuit and tube currents with a fault on the line (2-3). Neither tube operated, indicating the perfect selectivity.

Conclusions

In principle, super-frequency control has four inherent characteristics which contribute to its value. First, high-frequency currents "know more about reactance" than those of low frequency, which means that the small differences in line reactance which describe the distinction between a fault or normal load may be more easily detected with high frequency. In the second place, by the use of certain high-frequency blocking devices placed in the lines, a network having any degree of complication may be broken up into a number of simple networks at the high-frequency, each of which may be independently measured. This possibility provides a high degree of selectivity between

various lines, and independent isolation of faulty conductors without the drawback of time delay.

The third characteristic is that, inherently, high-frequency currents reach their peaks or relay operating values more rapidly than those of normal frequency, thus insuring a high speed of relay operation. Finally, the high-frequency superimposed currents measure the

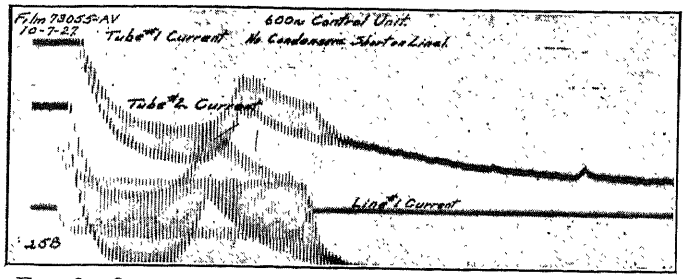


Fig. 8—Oscillogram of Relay Action with High Frequency Alone

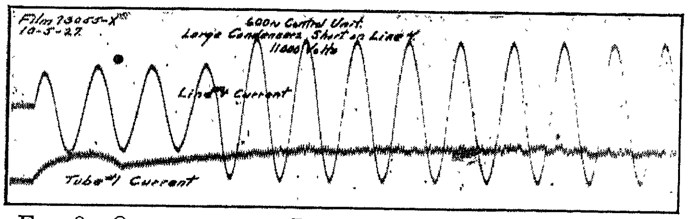


Fig. 9—Oscillogram of Relay Action Under Short Circuit Condition

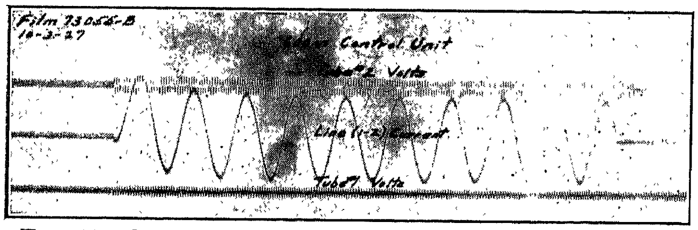


Fig. 10—Oscillogram of Voltage Across Relay During Short Circuit

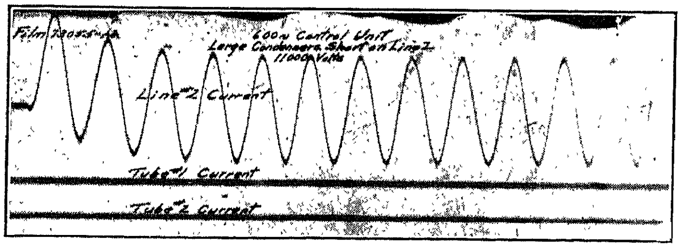


Fig. 11—Oscillogram Showing no Relay Action With Short Circuit on Parallel Line

pure impedance of a network, which is not possible with low frequency because of the counter-electromotive force of connected machinery. The advantage of the latter is an independence on the part of the superimposed system of all conditions of loading previous to a fault, an advantage which enhances recognition of fault conditions.

These inherent advantages lead to many possibilities. In general, the margin by which relays operate or do not operate may be considerably extended. Furthermore, the elimination of many variables in the power circuit by the use of high frequency makes possible accurate and simple calculation of relay operating currents. There are no particularly new principles involved and the system is simple enough to make possible its application to many of the more complex problems in circuit-breaker control.

A great many variations of this super-frequency control are possible, and have entered into experimental work and calculation. The system described has been used in an experimental way only, in order to demonstrate the soundness of its theoretical nature. The results obtained have been interesting and unique, and in themselves predict the future development of a super selective relay equipment.

Discussion

O. C. Traver: Mr. Ludwig's paper is very gratifying, not only on account of its definite contents but because of the goal sought. In the hope that it may help in the final solution of the problem, some of the handicaps that must be overcome are mentioned below.

Static and steep wave fronts will probably be very unwelcome on lines equipped with this protection. They might be expected to produce the requisite rate of rise to open the breaker on a perfectly good line.

Higher system voltage and frequency also work their hardships, chiefly from the standpoints of costs of the condensers.

The length of the trial line is not given. It is assumed from the general description to be relatively short. As the length increases the difficulties will multiply. Not only will the line reactance become objectionable, but to hold two 500-cycle generators in synchronism over a 100-mi. line, that is one-fourth cycle apart, would seem difficult. The greatest difficulties are apparent.

The use of the rate-of-rise relay suggests that the 500-cycle generators might sometimes fall out of step. Such condition might be fatal to protection should a fault occur during that interval.

The vacuum-tube relay, on its own account, is a very interesting development. It may not be as accurate as mechanical relays, but its speed will commend it, nevertheless.

R. G. McCurdy: As Mr. Ludwig indicates in his paper, telephone engineers are interested in any developments which increase the speed of relay and circuit-breaker operation on power transmission circuits, as such developments tend to minimize the interference which may be caused on adjacent telephone lines, during periods of fault or other abnormal operating conditions.

The schemes discussed by Mr. Ludwig, however, while obtaining a desirable result in improving conditions as regards interference under abnormal power conditions, may cause a considerable increase in noise interference on exposed telephone circuits under normal power-circuit conditions. It seems necessary that in order to make any superimposed high-frequency system function satisfactorily, the magnitude of the superimposed currents must be large as compared to the currents normally present on the power circuit in the same frequency range. It is evident, therefore, that the addition of such control currents employing frequencies in the range used for telephone transmission will increase the telephone interference factor of the power circuit and correspondingly increase the difficulties of coordination with adjacent telephone lines. Assuming 500-cycle voltages of the order of two per cent of the normal frequency voltage, as suggested in Mr. Ludwig's paper, this may result in

an increase of the telephone interference factor of the power circuit of the order of 3 to 1.

The efforts which have been carried along for the past few years on the part of the power and telephone companies have been effective in reducing both the influence of the power systems and susceptiveness of the telephone systems. It seems very important that any developments for improving the operation of relay systems which would reduce interference under abnormal power conditions shall be worked out in some way which would not involve at the same time an increase in the influence under normal operating conditions. In the application of high-frequency relaying schemes to power circuits it seems important from the standpoint of inductive coordination that either (1) continuous use of the high frequencies be avoided and their application to the system be confined to the sections of line in trouble and for the period while the trouble persists, or (2) that the control currents, if continuous, shall be at such frequencies and power levels as not to interfere with adjacent communication circuits. It would appear that this latter arrangement must in general mean a considerable reduction of the incidental currents of the power circuits near the frequencies involved.

D. W. Roper: I should like to inquire if this system can be used for the protection of lines that are entirely underground. I should also like to inquire how the system could be extended, if at all, so as to cover the most awkward case we have in our system in Chicago.

The most awkward system we have for relay protection is on high-potential transmission lines between generating stations—perhaps I should call them tie lines. The stations are of a capacity of upwards of a hundred thousand kw. apiece. There are transformers at both ends, and the lines are all underground cable. The 12-kv. connecting cable may be a few hundred feet up to two thousand feet from the switch to the transformer. The high-potential transmission line 66 kv. may be something of the order of 10 or 20 mi., and then there is at the other end some 12-kv. cable up to, say, 2000 ft. in length.

There are several systems which apparently work fairly successfully for opening the switches if the fault occurs on the high-potential line. The awkward case is where the fault occurs on one of the 12-kv. lines.

I should like to inquire of the author if it appears feasible to extend the application of his system to this particular case.

Paul MacGahan: The first impression obtained from the synopsis, and also from a superficial reading of the paper by Mr. Ludwig, is that in this superimposed high-frequency protection scheme there is a means which would be an improvement upon the present relay practise as regards transmission lines and feeders.

I doubt very much whether the author of the paper had this in mind, because the applications described are apparently upon networks of trolley conductors such as for the more complicated railway electrification systems.

It might be confusing to many, and result in unwarranted or at least premature hopes for further improvements in sectionalizing of feeders and transmission lines, to retain such an impression. While such a development might be possible in the future, it seems to me that the complications, such as, for example, in supplying an unfailing source of high-frequency power, synchronized on each bus, would be very hard to overcome and that, therefore, the proper place for this scheme of relay development is for cases that cannot be handled by means of the present highly accurate overcurrent time-element relays, and directional relays, or impedance relays.

Since the invention by the writer of the well known reverse-power relay, consisting of a sensitive watt element, the contacts of which are in series with the contacts of the overcurrent element, together with the duo-directional contact idea, there have been many mechanical and electrical improvements in the relays themselves and a great experience built up in their proper application, so that now there are few cases which could not be satisfactorily taken care of by the modern relays.

G. B. Dodds: In working out the details of construction and application of the relay equipment used, considerable attention should be given to the reliability of this equipment so that its addition to the system will not create an additional hazard.

This applies particularly to the construction of the blocking reactors and the manner of connection to the high-tension lines. In the past, considerable grief has been caused by the failure of choke coils connected in high-tension lines and the possibility of a recurrence of this experience should be carefully avoided.

One question which comes to mind is the method of synchronizing the high-frequency generators located in different substations. Can this be done by the use of the existing power-frequency potential transformers? In connection with the question of synchronizing there is a question in our mind whether a dash-pot relay would be suitable to prevent operation on synchronizing current, as it has been our experience that dash-pot relays are not entirely reliable.

The fact that a protective installation of this type can be tested in the field without actually drawing short-circuit current is greatly in its favor. Several power companies consider field testing of relay installations by actually grounding the lines very much worth while, and this testing would be very much facilitated in an installation of this kind.

It occurs to us that in connection with a protective installation of this nature some sort of back-up protection would be necessary, since if the protective equipment on a line failed to function, or a breaker failed to open and stuck in the closed position while a fault was on the line, there would be nothing to clear the fault from the system, as other high-frequency relays would not obtain sufficient current to operate. Of course this same situation exists in any type of balanced protection and is called to mind here only to point out that the current transformers used for the high-frequency relays should if possible be of such type that overload relays could be used in conjunction with them.

As the author states, a great many variations of high-frequency control are possible and it is to be hoped that among these variations one will be found that embodies simplicity and reliability of equipment and operation along with reasonable cost and maintenance. The scheme described by the author has its possibilities and should be developed.

D. W. Roper: I should like to ask the author if his scheme of relay protection is applicable to a case which is found in Chicago and other large cities. This case covers high-tension tie lines between generating stations in which the generators are operating at about 13 kv., 3-phase. Transformers located at each generating station change the pressure from the bus voltage to the transmission voltage which may be from 2 to 5 times the generator voltage. The connections between the transformers and the circuit breakers in the generating stations, as well as the entire high-voltage transmission line are underground, lead-covered cables. The protection of the high-voltage transmission cable is not particularly difficult, but this can not be said regarding the lengths of about 1000 ft. of 13-kv. cable at each end of the line forming the connections between the outdoor transformers and the oil circuit breakers. If a failure occurs on one of these cables at one station, for example, the oil circuit breakers at this station will be opened very promptly by the action of the relays; but if the relays at the other station are set low enough to operate under this condition, then they will also operate and open the line in case of through faults when there is no trouble on this transmission line.

J. R. Coffin: (communicated after adjournment) The method which Mr. Ludwig has used for obtaining a source of the high-frequency current (see Fig. 1 of his paper) is to provide at each switching station a small synchronous motor-generator set, the motor being driven from the power frequency of the supply

line and the generator operating to produce the high-frequency control potential.

The use of these small motor-generator sets involves certain disadvantages which it is believed could be eliminated by the use of another method of producing the control frequency. These disadvantages are as follows:

1. The problem of proper supervision and maintenance for these numerous small synchronous motor-generator sets would be serious, especially if used as indicated in a-c. railway transformer substations, which ordinarily do not have skilled attendance.

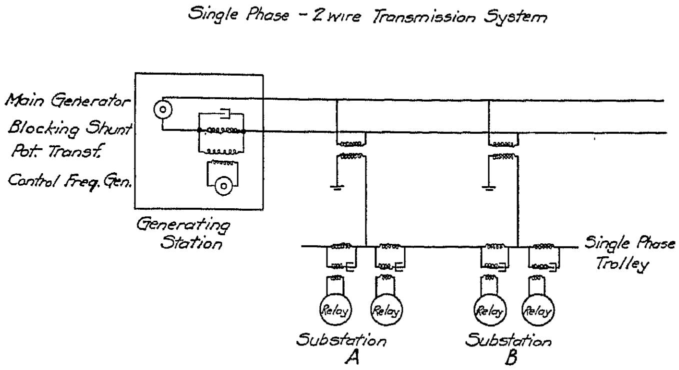


FIG. 1—APPLICATION OF CENTRAL SOURCE OF CONTROL FREQUENCY TO SINGLE PHASE A-C. RAILWAY SYSTEM

2. The problem of transient interchange of synchronizing power between high-frequency generators at adjacent substations has been covered by Mr. Ludwig in his paper. The presence of these transients requires the introduction of a certain amount of time delay into the relay system which would otherwise be unnecessary.

3. The problem of sustained interchange of synchronizing power between high-frequency generators at adjacent substations is also referred to in Mr. Ludwig's paper. This interchange of power arises because of the phase difference of the power frequency at adjacent substations due to transmission of load along the transmission system, which causes a phase displacement of the motors of the small motor-generator sets. This phase displacement in electrical degrees would be carried over into the high-frequency generators and multiplied by the ratio of the frequencies, so that a relatively small phase displacement in the power frequency would give rise to a much larger displacement in the control frequency. For example, in a railway system operating at 25 cycles a phase displacement of 2 deg. between adjacent substations in the 25-cycle frequency would cause a phase displacement of 40 deg. in the 500-cycle control frequency, which, of course, would result in a relatively large interchange of synchronizing power between the two high-frequency generators. In order to overcome this difficulty Mr. Ludwig has suggested the use of flexible spring couplings in the motor-generator sets. This would permit a reduction of the synchronizing power between adjacent high-frequency generators but it would quite possibly introduce other difficulties due to excessive hunting of the high-frequency generators.

4. Any electrical fault which developed in one of the small motor-generator sets would appear to the relay system as a bus short circuit at the substation and in the absence of special protective devices would result in the isolation of the substation even though no real fault existed on the power system.

The objectionable features just outlined could be avoided and advantages in the way of economy and reduced maintenance could be obtained by substituting a central source of high-frequency potential for the individual motor-generator sets at the substations. Referring to the accompanying Fig. 1, which for the sake of simplicity has been made applicable to a single-phase a-c. railway system, it will be noted that the small motor-generator sets have been eliminated and replaced by a single high-frequency generator located in the main generating plant where presumably it would operate under the most favorable conditions as regards supervision and maintenance. This high-frequency generator introduces into the transmission system a control frequency, the phase position of which at each substation is independent of the load which is being transmitted over the system. This control frequency passes through the ordinary substation transformers and reaches the trolley system without the necessity of any special apparatus at the substation except the small resonant shunts which are used to operate the relays. There is no tendency for a flow of synchronizing power either transient or sustained between the various substations. Should any trouble develop on the control frequency generator in the main generating station, the high-frequency potential would cease, and of course, the system would be left without relay protection until the control frequency was restored. However, the failure of the high-frequency generator would not in itself cause any interruptions or unnecessary circuit-breaker operations. A further advantage accruing from the use of a single high-frequency generator at a central location is the possibility of employing more elaborate apparatus to ensure constant control frequency. As the resonant circuits employed in this system are very sensitive to changes in frequency, difficulty might be experienced due to changes in the power frequency if the two frequencies are mechanically connected through the motor-generator sets.

Fig. 2 herewith, shows the application of the same idea to a d-c. railway system with three different types of a-c.—d-c. substations. The simplest case would be a synchronous-converter substation, as the control frequency would pass directly through the converter and no special apparatus would be required except the relays and resonant shunts. In the case of a

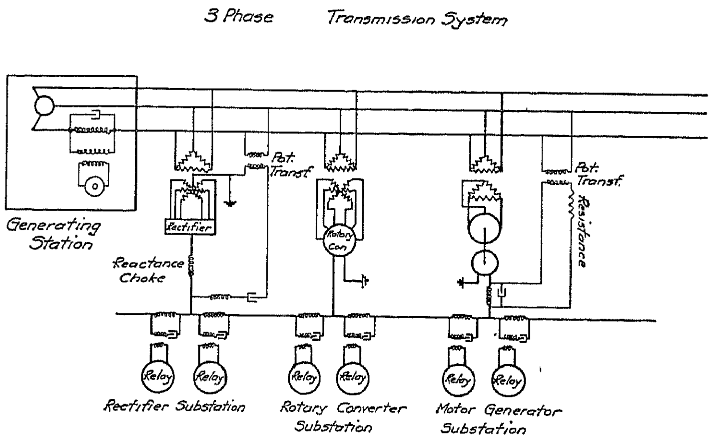


FIG. 2—APPLICATION OF CENTRAL SOURCE OF CONTROL FREQUENCY TO D-C. RAILWAY SYSTEM

rectifier substation there would ordinarily be a reactance choke on the d-c. side of the rectifier which would prevent the passage of the high-frequency control current. In this case the high-frequency control potential could be placed upon the trolley by the use of a potential transformer on the transmission line and a resonant filter circuit applied to the trolley, this resonant filter circuit being designed to pass only the control frequency. An alternate method would be simply to by-pass the reactance choke with a resonant filter circuit, omitting the potential transformer. Resonant shunts for the relays would be required as in the case of the other types of substations. For a motor-generator substation the method of placing the high-frequency control poten-

tial on the trolley system would involve the use of a potential transformer on the transmission system and a blocking shunt in the generator lead. A resistance in the secondary circuit of the potential transformer would also be required. The blocking shunt would then short circuit any frequency which might be present in the transmission system except the control frequency and this control frequency would appear on the trolley system. Resonant shunts in connection with the relays would be required as before.

In Mr. Ludwig's paper it is assumed that the various loads which might be placed upon the transmission system would have relatively low admittance to the control frequency and therefore would not admit a sufficient amount of the control-frequency current to cause difficulty in discriminating between a load and a fault. This assumption seems to be open to question. Assume, for example, that the load is of the order of 10,000 kv-a., and that the source of high-frequency current is of about 10-kv-a. capacity. If the load consists of a transformer and synchronous motor it would have a 25-cycle leakage reactance of perhaps 30 per cent on a 10,000-kv-a. base, which would give a 500-cycle reactance of 600 per cent on a 10,000-kv-a. base, or 0.6 per cent on a 10-kv-a. base, as compared with about 20 per cent in the high-frequency generator itself. The load would of course have no generated counter e. m. f. at 500 cycles. From these figures it seems that the load would appear substantially as a dead short circuit to the control system. This difficulty can be corrected by using a resonant blocking shunt in series with each load.

The use of a blocking shunt on the load suggests the use of a second control frequency for load indicating purposes. For example, in a railway system the locomotive could be equipped with a resonant shunt which would block the relay-control frequency but pass the load-indicating frequency. The load-indicating frequency current could operate a relay which would energize the substation whenever there was a locomotive in the line section on either side and deenergize it when both line sections were clear. Suitable interlocking arrangements between the two sets of relays to prevent energizing the substation upon the occurrence of a fault readily suggest themselves. As this system of automatic substation control depends only upon the position of the load and not upon its magnitude, it would not be subject to complications on account of locomotive regeneration.

Fig. 3 in Mr. Ludwig's paper indicates a method which might be used to introduce the control frequency into the line at a switching station where there was no transformer. It would seem that equally good results could be obtained with less complication by using a potential transformer and directional over-current relays of the usual type. The over-current element and the current coil of the directional element would be energized by the control-frequency current. The potential coil would be energized by line potential through the potential transformer. Each element of the relay would therefore respond to the control frequency only.

E. A. Hester: There is one point touched on by Mr. Dodds to which I should like to add a word, and that is the possibility of testing this particular type of protection without actually placing a fault on the system and drawing power current.

In Pittsburgh, we have a network of about the usual complication and we have had a great deal of trouble with grounds. There was a time not so long ago when we tried to predetermine what would happen under various conditions and then set the relay for those conditions. Consequently, many things were overlooked and we had considerable trouble resulting from the operation of the wrong ground relay and often important customers might be shut down.

Finally we decided the only thing to do was to put on actual fault to ground on the line and check the operation of the relays. This is usually done very late at night or at some time of minimum load and by pre-arrangement. Consequently, it is a real hardship on our protection engineer in his organization to get every installation tested. However, within the past two years, we have actually tested most of the installations by putting a ground fault on the line and we have reached a degree of reliability which we once thought we would never be able to reach. I do not mean to say that we have solved the protective problem, but we have found a way to achieve real results with the equipment now available. However, if some means can be found to eliminate the difficulties attending the making of arrangements to make tests at off hours it will be welcomed most heartily and the scheme described by Mr. Ludwig offers real possibilities.

L. R. Ludwig: The points brought out in the discussion of this paper have been very well taken, and serve to clarify the problems which were encountered in the development of this system.

Mr. Traver has properly stated that steep wave fronts may be unwelcome on lines equipped with this protection. They are harmless, however, if the high-frequency supplied energy is kept larger than the energy carried by these wave fronts. In tests, transformer-magnetizing-current transients and transients due to arcs, have been deliberately obtained without causing faulty relay operation. Higher system voltages and frequencies do work their hardships, and it is possible that the major utility of this system will be found in its application to railway networks where voltages and frequencies are low, and the high degree of circuit complication dictates comprehensive protection. The length of the trial line described was about seven miles. On such a line it is feasible, and cheaper, to synchronize the generators. For long lines such a procedure would, of course, be impractical, but unnecessary because two or more frequencies may be used with a modified circuit not described in the paper to obviate synchronizing. The rate-of-rise relay has a dual purpose as described, and will prevent relay operation in case the generators are somewhat out of phase, but does not imply that the generators are allowed to fall out of step, which is not the case.

Mr. McCurdy questions the effect on telephone lines of the normal high-frequency currents. Assuming as he does a 500-cycle voltage of two per cent, the telephone interference factor is 30. He has apparently compared this with a factor of 10, which is the best obtainable with pure sine waves. In practise, because of transformer magnetizing currents, etc., systems operate with factors of 20 to 40 regularly. Furthermore, a two per cent voltage is high because the drop in the impedance shunts has been neglected. Also, the telephone interference factor does not tell the entire story, since obviously the ampere-miles of inductive effect cancel out with currents flowing into a section from both ends, and the through-feed currents are necessarily very small because of the impedance shunts. From these facts it is logical to reason that the problem of telephone interference is neither serious nor insurmountable. The problem is further simplified by the fact that the currents are hardly continuous because there are times of light load when practically no high-frequency current will flow. The frequency of 500 cycles, while low on the curve of telephone interference, may not be the best for ultimate use.

Mr. Dodds has raised a necessary question in regard to applying high-frequency apparatus to the lines in such a way that additional hazards are not created. Much depends upon the system to be protected; if it is possible to use small line reactors, they may be connected directly in the line, whereas larger ones would require mounting in a tank of oil equipped with suitable bushings. With regard to synchronizing the generators, this is most easily done by throwing them together regardless of phase position, and letting them pull into step. The dashpot relay has not been used in the form described in the paper, which was diagrammatic, but the relay may gain its time element by electrical means; that is, a mechanical relay may be used in conjunction with the pre-setting transformer shown in Fig. 6. Straight

overload relays for back-up protection should be used as pointed out by Mr. Dodds.

Mr. Roper has presented an interesting problem and inquired if a solution is possible by the use of high frequency. So far no tests have been made with cables, and because of their special properties, some difficulties may be encountered. For example, the high-frequency charging current and the effect of the cable capacity will influence the control currents, though there are means of taking these influences into account. So far as the circuit shown is concerned, adequate protection could be secured by properly introducing and blocking the high frequency, but the question regarding cables is at the present time an unanswered one.

Mr. Coffin is correct in stating that there are certain disadvantages in the use of a number of high-frequency generators. This is, however, the most flexible arrangement, and was illustrated because it is applicable to almost any system. In some of the less complicated circuits, numerous simplifications of the system are possible, one of which is shown by Mr. Coffin in his Fig. 1. There is a difficulty in the application shown in this figure, however, which prevents it from being general. Under fault conditions the control current must flow through the high line and transformer, which have considerable impedance. If this impedance is high compared to that of the connected load, it will be impossible to discriminate between load and fault conditions. Blocking shunts in the load circuits could be used as mentioned by Mr. Coffin, but their use was abandoned because of the large expense which they entail due to their being numerous. This point is further clarified by Mr. Coffin's discussion regarding the admittance of loads. The reactance of the load is, in principle, correctly compared to the reactance of the high-frequency generator itself, but reactance in the circuit supplying control current to the lines is disadvantageous in the same way as the leakage reactance of the generator.

In the case of the synchronous-machine load calculated by Mr. Coffin, the figures do not seem complete because the high-frequency and normal-frequency reactances are compared in per cent without taking into account the fact that the voltages at the two frequencies are different. Suppose, for example, that the synchronous motor is supplied from an 11,000-volt line, to which a 250-volt high-frequency generator of 10 kv-a. is connected. The 0.6 per cent reactance of the load as calculated by Mr. Coffin must be multiplied by the ratio of the voltages squared, or the reactance is over 1100 per cent, 53 times that of the generator itself. Calculation using actual ohms impedance yields the same result. In general, the assumption that the load impedance is higher than the line impedance is correct.

The use of high frequency for load-indicating purposes is feasible, and in fact, was one of the first suggested applications of the system described.

The use of a potential transformer for introducing high-frequency currents into protected lines has the objection that the small transformer has too much reactance to permit differentiation between load and fault conditions. A condenser would need to be used with the transformer to neutralize its reactance. Directional relays as suggested, as well as interlocked high- and low-frequency relays, have been used but do not generally seem necessary.

Extinction of an A-C. Arc

BY J. SLEPIAN[1]

Fellow, A. I. E. E.

Synopsis.—The transition from high conductivity to high resistivity which an a-c. arc undergoes on extinction is studied. Theory and approximate calculations are given for the rate of recovery of dielectric strength of the arc space for short arcs, and results are given of experiments on short arcs, and arcs in holes and slots in insulating material and insulating plates. The influence of chemical activity in arc gases is discussed. Factors contributing to the success of the a-c. oil circuit breaker are suggested.

1. Introduction

THE extinction of an a-c. arc as it is effected in switches and circuit breakers operating in a-c. circuits is fundamentally very different from the extinction of the arc in a d-c. switch. In the latter, by lengthening or otherwise, the arc is brought into such a form that it requires for its maintenance a voltage higher than is generated in the d-c. circuit. The current then decreases, and if the voltage required by the arc remains higher than the generated voltage, the current reduces to zero and the arc is extinguished. In the d-c. switch, then, it is important that the arc voltage be made and kept sufficiently high.

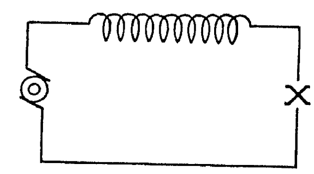
In the a-c. switch, however, the arc while it is playing takes a voltage which is generally smaller than the voltage generated in the circuit, and influences the course of the current only in a minor way. The current following its natural cycle comes to a zero value, and at such a moment, the arc extinguishes. In a very short interval of time embracing this moment of zero current, the medium containing the arc returns from its momentary condition of a comparatively good conductor, carrying current at a low voltage, to its normal condition of a comparatively good insulator supporting the full generated voltage of the circuit with passage of little current. It is this rapid transition at the moment of zero current, from the state of a highly conducting arc to the state of an insulating non-ionized gas which is important for the extinction of the arc in an a-c. switch. This transition must be made sufficiently rapidly if the arc is not to reestablish.

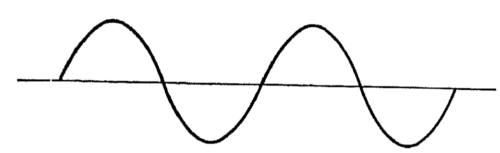
The study of this transition from arc to insulating gas at zero current is therefore not only interesting in itself but is important in that it may reveal principles leading to improvements in a-c. circuit breakers. This paper covers ideas on this subject developed by the author and his co-workers during the past few years.

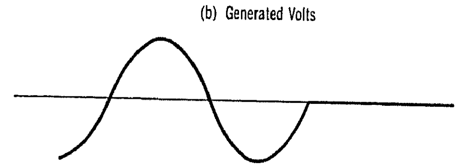
2. Transition Time and External Circuit

We shall first consider the question of the time available for the transition from arc to dielectric at the current cycle end in a circuit breaker operating in a practical reactive circuit. It is quite clear that this transition requires a finite time to be effected, that it cannot take place instantly. The conductivity of the medium carrying the arc cannot disappear suddenly. Being due, as we shall assume in this paper, to the presence of ions, time must be given for these ions to disappear, either by neutralizing their charges among themselves by recombination, or by discharging into the electrodes. Now how much time is available for this deionization in a practical circuit?

Consider first the circuit of Fig. 1, consisting of an


(a) Circuit with Ideal Reactor


(b) Generated Volts


(c) Current

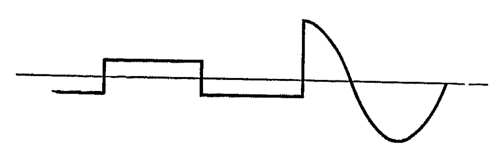

(d) Arc Voltage

FIG. 1

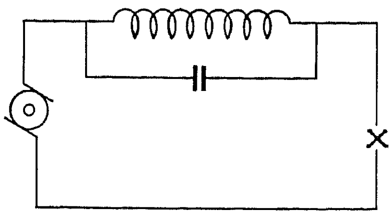
a-c. generator of large capacity, in series with a reactor and an arc. Assuming that the arc voltage is small compared to the generator voltage, the current will lag by nearly 90 deg., as in Fig. 1C. The voltage across the arc will of course be in phase with the current, as in Fig. 1D. Now if at the end of a half cycle of current, the arc should extinguish and the current remain zero, the voltage across the electrodes would at once rise to the terminal voltage of the generator at that time, and because of the phase relationships this would be the peak of the generated voltage. Hence, in such a circuit, no

1. Consulting Research Engineer, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

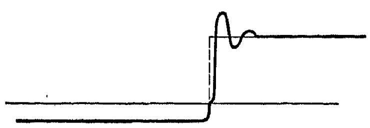
Presented at the Summer Convention of the A. I. E. E., at Denver, Colo., June 25-29, 1928.

time whatever would be allowed for the arc to lose its conductivity at the end of a current cycle. If the arc extinguished then, the space would immediately have to support the full generated voltage. An arc whose voltage is low relative to the generated voltage could not extinguish in such a circuit.

However, it is only an ideal reactor which could act to produce the results just mentioned. Every actual apparatus must have electrostatic capacity as well as inductance. An actual reactor may be considered as



(a) Circuit with Actual Reactor



(b) Arc Voltage

Fig. 2

acting as if it were an ideal reactor shunted by a small condenser, as in Fig. 2A. With such a shunted reactor, the voltage across the arc space will not rise instantly after arc extinction to the generator value, but will come on gradually as the reactor undergoes an oscillation. This is shown in Fig. 2B, on a time scale much expanded as compared with Fig. 1. The time for the voltage impressed across the arc terminals to reach generated voltage is one-quarter of the period of a natural oscillation of the reactor. This we may call the time available for the transition from the conducting arc to the insulating gas space.

This result can evidently be generalized, and we may say that the time available for transition is always as great or greater than a quarter of a period of free oscillation of the circuit external to the arc. In practical power circuits, the frequency of free oscillation may vary from the order of 100,000 cycles per sec. for the case of a current limiting reactor to only a few hundred cycles for the case of a very long transmission line. The time available for the extinction process in the arc, varies then from 2.5 microseconds to several thousand microseconds depending on the character of the external circuit.

It would seem from this that the interrupting capacity of an a-c. switch may under certain conditions be greatly affected by the nature of the circuit in which it operates.

In experimenting on the extinction of a-c. arcs it proved desirable to control the time available for the extinction of the arc. This was readily accomplished by shunting the arc with an adjustable resistance as shown in Fig. 3. In this circuit, immediately after arc extinction the voltage V, rises to the generator voltage value following the exponential curve,

$$V = V_0 \left(1 - e^{-\frac{Rt}{L}}\right) \tag{1}$$

We may take $\frac{L}{R}$, the relaxation time, as the time available for the transition.

The initial rate of rise of voltage impressed upon the arc space as given by equation (1) is

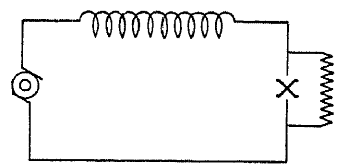
$$\frac{dV}{dt} = \frac{V_0 R}{L} \tag{2}$$

The symmetrical short circuit current of the circuit is $I_0 = \frac{V_0}{L\,\omega}$, and the current which flows through the resistor after the arc is extinguished is $I_R = \frac{V_0}{R}$.

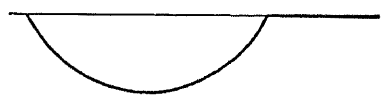
Hence the initial rate of rise of the impressed voltage is also given by

$$\frac{dV}{dt} = V_0\, \omega \frac{I_0}{I_R} \tag{3}$$

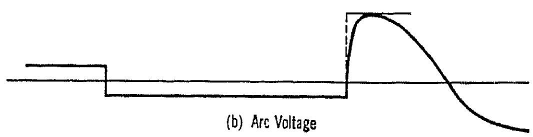
This initial rate of rise of voltage may also be taken as a measure of the time available for the transition, since the arc space must recover dielectric strength at a rate



(a) Circuit with Shunted Arc



(b) Arc Current



(b) Arc Voltage

Fig. 3

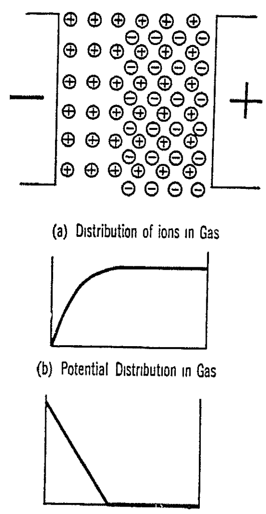
sufficient to withstand impressed voltage growing at the rate given by equation (2) or (3).

3. The Electric Gradient in an Ionized Gas Between Closely Spaced Electrodes

In the last moments of the arc current, and immediately following the current zero, the factors producing new ions have in general ceased their activity, and the ions already in the gas are rapidly diminishing in number by recombination. The rising voltage impressed upon the arc terminals by the external circuit

acts therefore upon a gas space containing a diminishing density of ionization. The question then naturally arises as to what is the dielectric strength of an ionized gas as a function of its density of ionization.

Important in the determination of the dielectric strength is the distribution of the electric gradient in the ionized gas. It is at once clear that the distribution will not be a uniform one. Although, initially, the densities of the positive ions and negative ions may have been everywhere equal, as a result of the application of the electric field this equality is disturbed, and space charges appear which cause the electric field to be distorted. At the cathode negative ions are repelled, and positive ions are attracted. A positive space charge therefore develops in front of the cathode which increases the electric gradient there. Similarly at the anode, a negative space charge and increased gradient also develops.



(a) Distribution of ions in Gas

(b) Potential Distribution in Gas

(c) Gradient Distribution in Gas

Fig. 4

The exact calculation of this gradient distribution is very difficult, although much has been done on this problem by J. J. Thomson, J. S. Townsend, G. Mie, and others.[2] However, we may arrive at a sufficiently good approximation to the gradient distribution for our purposes in the following way. The mobility of the positive ions in the electric field is very small compared to the mobility of the negative ions, which are electrons in the cases in which we are interested. We shall therefore neglect entirely the motion of the positive ions and consider them fixed in space. The negative ions, however, we shall suppose move freely under the influence of the electric field.

With these hypotheses, the effect of the electric field is to move electrons away from the cathode as in Fig. 4, exposing a space charge of positive ions in front of the cathode with charge density, $n\,e$, where n is the number of positive ions per cm.[3], and e is the charge of an ion. This space charge causes a considerable portion of the impressed voltage to be consumed in the region next to the cathode. The thickness of the space charge will grow until all the impressed voltage is consumed in the cathode space. Assuming now that the diameter of the section of the ionized gas is large compared to the distance between the electrodes, we may apply Poisson's equation for one dimension and taking $e = 4.77 \times 10^{-10}$ e. s. u. we readily arrive at the following relations.

Thickness of space charge, d,

$$d = 1.05 \times 10^{3} \sqrt{V/n} \qquad (4)$$

Gradient in space charge at distance x from cathode,

$$\frac{d\,V}{d\,x} = 1.8 \times 10^{-6}\, n\,(d - x) \qquad (5)$$

Maximum gradient in space charge

$$\left(\frac{d\,V}{d\,x}\right)_{max.} = 1.89 \times 10^{-3} \sqrt{V\,n} \qquad (6)$$

Mean gradient in space charge

$$\left(\frac{d\,V}{d\,x}\right)_{mean} = 0.95 \times 10^{-3} \sqrt{V\,n} \qquad (7)$$

These equations will apply of course only if the thickness of the cathode space charge as given by equation (4) is less than the distance between the electrodes.

4. First Approximation to the Dielectric Strength of an Ionized Gas Between Closely Spaced Electrodes

As a first approximation we may assume that electrical breakdown of the ionized gas will occur if the maximum electric gradient in it exceeds a certain critical value. For the sake of definiteness let us take for this critical value, a value approximately appropriate for air at normal pressure and temperature, namely 30,000 volts per cm. From equation (6) then it follows that breakdown will occur when

$$\left(\frac{\partial V}{\partial x}\right)_{max} = 1.89 \times 10^{-3} \sqrt{V\,n} = 30{,}000 \qquad (8)$$

or

$$V = 2.52 \times 10^{14} \times \frac{1}{n} \qquad (9)$$

The breakdown voltage then varies inversely as the density of ionization, and is independent of the distance between the electrodes, so long as the electrode separation is greater than d, given by equation (4).

If the gas is at temperature T, we may assume, still as a first approximation, that the critical gradient varies inversely as the absolute temperature. Equation (9) then becomes

$$V = 2.52 \times 10^{14} \times \left(\frac{273}{T + 273}\right)^{2} \times \frac{1}{n} \qquad (10)$$

2. *Handbuch d. Physik*, by Geiger and Scheel (published by Springer), Bd. XIV, page 6.

5. The Decay of Ionization in a Gas

During the transition period immediately after the current zero, the dielectric strength of the arc space is rapidly increasing due to the decrease in the density of ionization, as given by equations (**9**) and (**10**). For an arc in the open, the ionization disappears principally by recombination. The rate of loss of ions by recombination is given by

$$-\frac{d\,n}{d\,t} = \alpha\, n^2 \qquad (11)$$

where α is the coefficient of recombination.* The solution of this equation is

$$\frac{1}{n} - \frac{1}{n_0} = \alpha\, t \qquad (12)$$

where n_0 is the density of ions at time $t = 0$. Where n_0 is very large, as in the case of the arc which we are considering, $\frac{1}{n_0}$ is negligible, and (**12**) becomes

$$n = \frac{1}{\alpha\, t} \qquad (13)$$

The numerical value to take for α in this equation is rather uncertain. For air at normal pressure and temperature several investigators have found $\alpha = 1.3 \times 10^{-6}$ for "aged" ions. Plimpton[3] found values for α for ions aged 0.05 sec. and longer, and an extrapolation of his values for age zero would give α equal to about 7.6×10^{-6}. As for the influence of temperature at constant pressure, Phillips[4] has found the following variation in relative values at different temperatures.

Absolute Temperature..	289	373	428	449	546
α....	1.0	0.5	0.399	0.360	0.178

For our purposes, probably the best we can do is to take α inversely proportional to the cube of the absolute temperature.

6. The Recovery of Dielectric Strength in the Transition from an Arc. First Approximation, Short Arc

Combining the results of sections 5 and 6, we get from equations (9) and (13) taking $\alpha = 7.6 \times 10^{-6}$

$$V = 1.9 \times 10^9\, t \qquad (14)$$

If we take into account the influence of temperature assuming α varies as the inverse cube of the temperature, and that the breakdown gradient varies inversely as the temperature we get

$$V = 1.9 \times 10^9 \times \left(\frac{273}{T + 273}\right)^5 \times t \qquad (15)$$

Even allowing for the uncertainty of the numerical constants, these equations show that the recovery in dielectric strength is very rapid. In ten microseconds, if the gas is cold, the arc space is capable of withstanding several thousand volts. According to these equations a low voltage a-c. arc should extinguish in a circuit such that during the transition time the rate of increase of voltage applied to the electrodes is less than between 10^6 and 10^8 volts per sec.

Aside from the uncertainty of the constants used in the preceding development, the nature of the departures from the physical facts made in deriving this approximate theory should be borne in mind. First, it was assumed that the positive ions have zero mobility, and that the positive ion density in the cathode space charge is the same as that in the body of the gas. Actually, these assumptions are not true, and an attempt is made in the Appendix to take the mobility of the positive ions into account.

Second, it was assumed that there exists a critical breakdown electrical gradient for air, such that if this gradient is exceeded at any point, the gas will break down. Actually, however, although for larger electrode spacings for a given pressure, the mean gradient at breakdown is nearly constant, for short spacings the gradient at breakdown increases very rapidly as the spacing is decreased. In fact, as is well known, there is a minimum voltage which will produce breakdown regardless of electrode spacing, and for air this minimum voltage is about 300 volts. Account of this factor will be taken in a later section.

Third, it was assumed that the linear dimensions of the section of the ionized gas was large compared to the thickness of the cathode space charge. This will fail to be the case when very small alternating currents are considered or when the arc is confined to small holes or narrow slots, as will be shown in section 12.

7. Experiments on the Extinction of a Short A-c. Arc in the Open

Some time ago Mr. L. R. Golladay and the author made a study of the interrupting capacity of the multigap lightning arrester. This arrester consists of knurled brass cylinders spaced one-sixteenth of an inch apart, and some of the gaps so formed are shunted by resistors.

Tests on individual gaps were made in a circuit like that of Fig. 3. The arc was started by a small fuse wire, and the shunting resistor R was varied. For sufficiently low values of R the arc would extinguish at the end of the half cycle, but for large values of R, the arc would persist. The limiting value of R which would cause the arc to extinguish was determined for currents varying from 100 to 500 amperes, and voltages varying from 300 to 600 r. m. s. Tests were made both at 25 cycles and 60 cycles.

It was found that the limiting resistance varied inversely as the arc current, inversely as the frequency, and was approximately independent of the voltage.

*Townsend, *Electricity in Gases*, Oxford 1913, Chapter VI.

3. Plimpton, *Phil. Mag.* (6) V. 25, 1913, p. 65.

4. Phillips, *Proc. Roy. Soc.*, London (A) V. 83, 1910, p. 246.

These results applied to equation (**3**) show that $V_0\ \omega\ \dfrac{I_0}{I_r}$ was constant or that $\dfrac{d\,V}{d\,t}$ was constant. Thus the arc would extinguish if during transition the rate of increase of applied voltage was less than a critical value, and would persist if the rate of increase of applied voltage was greater than this value. This critical value was found to be 25×10^6 volts per sec.

It is interesting to compare this result with equation (**15**). A reasonable value to take for the temperature in the neighborhood of the cathode would seem to be the boiling point of brass or about 1200 deg. cent. Substituting in (**15**) we get $\dfrac{d\,V}{d\,t} = 0.4 \times 10^6$. If we take the melting point, or 940 deg. cent. we get $\dfrac{d\,V}{d\,t} = 1.1 \times 10^6$. These values are rather small compared to 25×10^6 but agree better with the results obtained in section 11, so that in these experiments perhaps a large part of the discrepancy is due to differences between the properties of zinc vapor and air, as the arc extinction probably took place in zinc vapor.

8. Chemical After-Effects in Gases from an Arc

The rapidity of recovery of dielectric strength of the arc space predicted by the preceding theory and confirmed by the experiments described in section 7, would seem to be contradictory with experience, as it is well known that gases coming from switch arcs frequently cause flashover of live parts, hundredths or tenths of a second after the gases have left the arc. However, it appears that it is a chemical activity in these gases because of their composition, which is responsible for their continuing low dielectric strength rather than the fact that they originated in an arc. Thus, in the copper arc, large volumes of copper vapor may be given off at the electrodes. This vapor will burn in air forming a flame. Since the burning as a flame involves the diffusion of oxygen of the air into the copper vapor, and since this is a relatively slow process, the burning of the flame may continue for a considerable time. Such balls of flame are frequently seen rising in the air after the extinction of the arc, when high speed pictures are taken of a copper arc, as for example in a commutator flashover. These flames have a low dielectric strength as long as they are burning. When arcs exist under conditions where little vapor or combustible gas is given off practically no persisting flame is observed after the arc is extinguished.

The substantiation of the above statements lies in studies made by J. E. McGee and L. Dennault, not as yet published.

9. Arcs Through Holes in Metal Plates

From the theory so far given, and accepting the experimental value of 25.10^6 volts per sec. as the rate of recovery of dielectric strength of the arc space, it would seem that an arc in the open air is not a practical means for interrupting a-c. circuits of voltages higher than a few hundred volts. For example in a 2300-volt r. m. s. circuit, the arc space would require 1.3×10^{-4} sec. to recover sufficient dielectric strength to withstand the peak voltage of 3250. Practical circuits in general will be faster than this, so that the arc will not extinguish. It is possible, of course, to slow down the rate of rise of the voltage applied to the arc terminals during the transition period by shunt resistors, and equation (3) shows that for 60-cycle current the resistors after the arc is interrupted need to carry only five per cent of the current interrupted. Nevertheless, even with this low ratio of resistor current to current interrupted, the resistors become very large and expensive for a high power switch, and for higher voltages the resistor current ratio rises proportionally so that matters become much worse.

It occurred to the author that conditions might be considerably improved if the arc was caused to play through small holes or openings in metal plates. In this way ions could disappear by discharging into the metal plates during the transition time, instead of having to depend only on the recombination in the gas space, and so the deionization would be greatly accelerated. Space charges would be produced in the neighborhood of each plate which would consume some of the impressed voltage so that each perforated plate would to a certain extent, act like a cathode as described in section 3. By having a number of these perforated plates in series, the rate of recovery of dielectric strength would be multiplied proportionally. It was believed, and subsequently substantiated that the arc could play through the perforations of the plates for several half cycles (60-cycle current) without melting the metal, whereas it was believed that the arc terminals were necessarily molten.

Many tests of these ideas were made by J. H. Neher and others. In one, as an example, nine sheets of 16-in. brass gauze, made of 0.032 in. diameter wire, were stacked parallel to each other between two solid copper plates, the sheets being separated by 1/16 in. insulating spacers. An arc of several hundred amperes drawn in a reactor circuit of 2200 volts 60 cycles was then blown into the structure by an air blast, the arc terminals being on the solid end plates and the arc stream playing through the holes in the gauze. Resistance in shunt was varied to determine the limiting value which would cause the arc to extinguish at the end of its first half cycle in the structure. In this way, it was found that the rate of recovery of dielectric strength in the structure was 80×10^6 volts per sec. or more than three times as fast as for an arc in the open. By using appropriate shunting resistors, current up to 1600 amperes at 6600 volts was interrupted by the structure.

Tests were also made on the rate of deionization occurring when the arc was confined to circular holes of

various diameters in plates of various thicknesses. Nine plates, each with a hole and two end plates, were stacked together with insulating separators 1/16 in. thick. The end plates were provided with very fine holes just large enough to pass a fine copper fuse wire. All the holes were lined up, and the copper fuse wire threaded through, and an arc started by short circuiting a small 2200-volt, 60-cycle generator, giving 200-amperes short circuit current, upon the fuse wire. Oscillograms were taken, and resistance in shunt to the fuse was varied so that it would just cause the arc to extinguish at the end of the first half cycle of current. From the oscillograms the rate of change of current, $\frac{dI}{dt}$ at the end of each half cycle was measured, and the initial rate of rise of applied voltage at transition was taken to be $R \frac{dI}{dt}$ where R was the value of the shunting resistance.

The results are given in the curves of Fig. 5. The

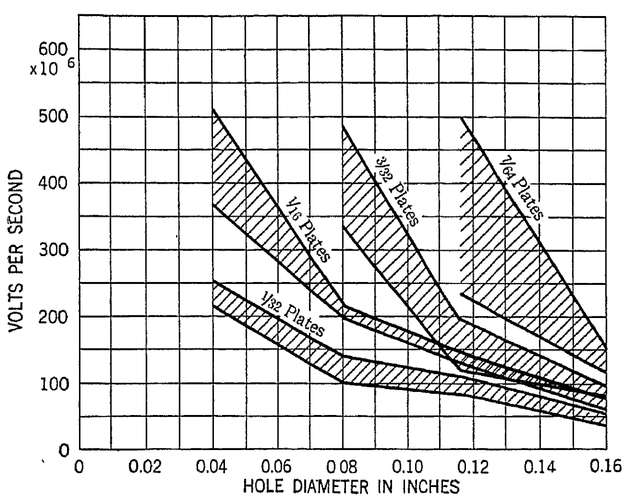


Fig. 5—Arc in Holes in Metal Plates

right hand boundary of each shaded region gives the largest rate of rise of applied voltage observed at which the arc did not restrike, and the left hand boundary gives the smallest rate of rise of applied voltage observed at which the arc did restrike.

As was to be expected, the smaller the diameter of the hole, the greater was the rate of recovery of dielectric strength, and for the small holes, values greater than 350×10^6 volts per sec. were obtained. This is 35×10^6 per sec. per plate, and seems to contradict the results of Golladay and Slepian mentioned in section 8, where 25×10^6 volts per sec. was found as the limiting value for a solid cathode. It was hardly to be expected that the perforated plates would act as well as solid plates.

The explanation is to be found in the low voltage per plate, less than 220 volts r. m. s. used in these tests as will be explained in the next section.

10. Recovery of Dielectric Strength of Short Arcs at Low Voltages

Equations (14) and (15) developed for an arc in the open, with solid cathode show that the arc space recovers dielectric strength at a constant rate immediately after extinction of the arc. Experiments at 300 to 600 volts r. m. s. with brass electrodes described in section 7, indicated that this rate of recovery was about 25×10^6 volts per sec. In deriving the equations (14) and (15) it was assumed that there was a definite critical electric gradient which if it was exceeded at any point, would cause breakdown and restriking of the arc. However, it is well known that the mean gradient at breakdown of short spark-gaps increases rapidly as the length of the gap decreases, and that even for very short gaps, breakdown does not occur with less than a certain minimum value of voltage. For air, this minimum breakdown voltage is about 300 volts, or about 215 volts r. m. s.

It might be expected then, that as the arc circuit voltage is reduced down towards the value 215 volts, r. m. s., the mean rate of recovery of dielectric strength will increase very rapidly, and that for voltages below 215 volts r. m. s., it will be of a different order of magnitude than for voltages much above 215 volts r. m. s.

The same conclusion may also be reached by way of the current ideas concerning the difference in mechanism of a glow discharge and an arc discharge. In the glow discharge, it is believed that all the ionization is due to collisions of ions caused to move with sufficient velocity by high electric gradients. In the arc, it is believed that other factors produce ionization, such as high temperatures, or direct action of 10^6 volt/cm. gradients upon the cathode, etc.[5] At the time the current passes through zero these other factors have ceased their activity. If the discharge is to restrike, it must restart as a glow. But the glow discharge requires for its maintenance a certain minimum voltage, the normal cathode drop, and this normal cathode drop is very nearly equal to the minimum sparking potential of the gas.

Thus, we again conclude that the first few hundred volts of dielectric strength are recovered almost instantly as compared with the recovery of the later increments of dielectric strength.

11. Experiments on Recovery of Dielectric Strength of Short Arcs at Low Voltages

The conclusions of the preceding section found confirmation in the following experiment. Sheets of copper were stacked together with 1/16 in. separators, and an arc of several thousand amperes in a circuit of adjustable voltage from 2300 volts down, was blown into the structure, thus causing a series of short arcs to

5. K. T. Compton, Trans. A. I. E. E., Vol. XLVI, 1927, p. 868.

be produced between successive sheets. A suitably disposed magnetic field then caused these arcs to move in an annular path, and the arcs retraced this path so rapidly that practically no melting or burning of the metal sheets resulted. Details as to the construction of these sheets and the magnetic field will be given in a later paper. As a result of the lack of melting of the sheets there was no flame of burning copper vapor to complicate the results as described in section 8, and it is probably correct to say that the arc extinction took place in air rather than in copper vapor.

The number of copper sheets was varied, also the circuit voltage and the value of shunt resistance which would just cause the arcs to extinguish at the first current zero was determined. From these values of shunt resistance, the rate of rise of applied voltage was calculated by equation (3) and the curve of Fig. 6 was obtained.

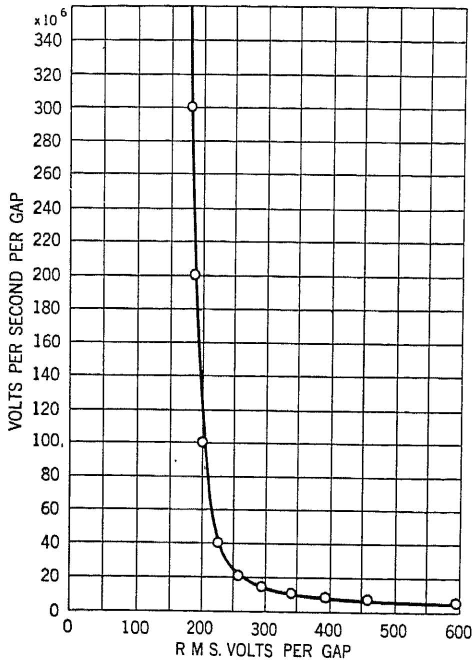


FIG. 6—RECOVERY OF DIELECTRIC STRENGTH OF SHORT ARCS IN AIR

For voltages per gap above 500 r. m. s. the mean rate of recovery of dielectric strength was 4×10^6 volts per sec. This seems to be very low compared to 25×10^6 volts per sec. observed by Golladay and Slepian for brass electrodes, but agrees better with the value calculated in section 7 thus indicating that air deionizes more slowly than zinc vapor. As the voltage per gap was reduced, the rate of recovery of dielectric strength increased reaching 300×10^6 volts per sec. at 180 volts per gap. For lower voltages per gap than this the rate of recovery could not be determined, as the arc would extinguish even when the shunting resistor was omitted.

The curve of Fig. 6 appears to have an asymptote at 165 volts r. m. s. corresponding to a peak of 235 volts. The normal cathode drop for copper in air is 252 volts.[6] Thus the conclusions of the preceding section are confirmed.

6. K. Rottgardt, *Ann. d. Phys.* Bd. 33, 1910, p. 1161.

12. LONG ARCS AND ARCS IN SLOTS AND HOLES IN INSULATING MATERIALS

Equations (14) and (15) state that the rate of recovery of dielectric strength of the arc space measured in total volts applied per second is a constant. In deriving this relationship, it was assumed however that the linear dimensions of the cross-section of the arc space were large compared with the distance between the electrodes. This is certainly not the case for long arcs, or for arcs compelled to play in small holes or slots in insulating material.

When the space charge region before the cathode is long compared with the linear dimensions of its section, Poisson's equation in one dimension cannot be applied, and it is no longer true that the maximum electric gradient, at the cathode, is a function only of the total applied voltage as is given in equation (8). The boundary of the space charge region is no longer a plane parallel to the cathode surface, but it tends to run up on the sides of the hole or slot as in Fig. 7. This makes even an approximate analysis very difficult, but it is hoped to deal with this in a future paper. A first study indicates that the voltage across the space charge sheath is of the same order of magnitude as the impressed *gradient* multiplied by the thickness of the slot or diameter of the hole. Hence we would expect the arc to extinguish if during the transition there is an almost instantaneous application of a *gradient* of the order of two or three hundred volts divided by the hole diameter or slot width.

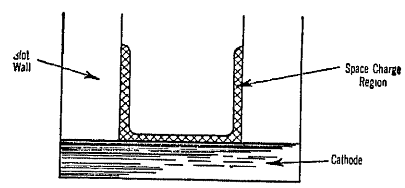


FIG. 7—SPACE CHARGE REGION FOR ARC IN SLOT

The curve of Fig. 8 obtained by Mr. R. C. Mason for slots and holes in soapstone one to two inches long roughly bear out this conclusion. The gradients given are those at which the unshunted arc would just extinguish at the end of the first half cycle. If we multiply this gradient by the width of slot we get for the different slot widths the following:

1/16 in. slot, 143 volts
2/16 in. slot, 146 volts
3/16 in. slot, 92 volts
4/16 in. slot, 63 volts

These are all at least of the right order of magnitude. Mr. Mason's results show that in narrow slot arcs can be interrupted in circuits of very considerably higher voltage than in the open air.

13. The Oil Circuit Breaker

The success of the oil circuit breaker in high power a-c. systems is probably due in part to all the factors discussed in the previous sections. Most important of all undoubtedly is the fact that the arc under oil is in an oxygen free atmosphere. Hence, in spite of the fact that quantities of hydro-carbon gases are produced by the decomposition of the oil, due to the lack of oxygen no persistent combustion flame follows the extinction of the arc at zero current.

The confining action of oil upon the arc raises enormously the impressed gradient at which the current

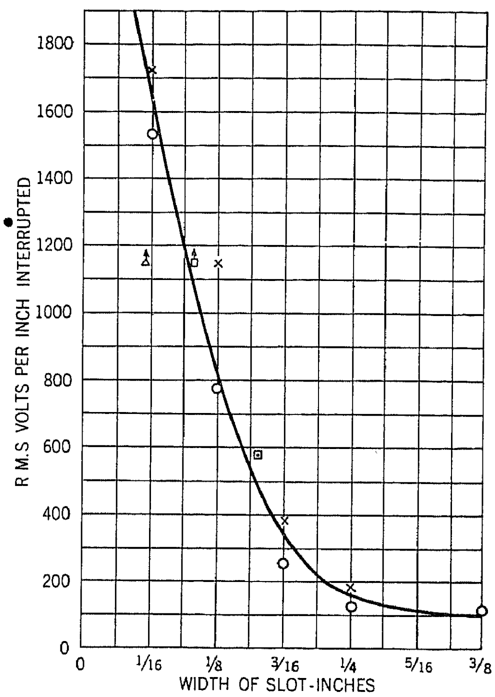


Fig. 8—Extinction of Arc in Slot

can be interrupted, just as the narrow slots did as described in section 12. The arc plays in a hydro-carbon gas "hole" through the oil, and at the time the current is passing through zero this "hole" may be of relatively small section.

Another factor which is very likely of considerable importance is the electrical conductivity of the hot oil immediately adjacent to the arc, and which probably contains decomposition products. The conductivity of this oil may be very large just at the moment the arc extinguishes, although of course, it would fall off very rapidly as the hot oil mixes with the cold oil about it. No information is available as to the magnitude of this conductivity but it seems very probable that it is sufficient to influence appreciably the rate of rise of applied voltage during the extinction process, as considered in section 2.

Still another possible factor is the influence during the extinction period of drops of oil or the carbonized residues of drops of oil floating in the arc space. These particles will form centers for the ions to discharge upon, very much as the wires of the gauze sheets in the experiment of section 9. Space charges will form in the neighborhoods of these particles which will tend to relieve the region immediately adjacent to the cathode from the high gradient which it would otherwise have.

14. Summary

The time interval allowed by the external circuit for the arc space to recover its insulating properties after a current zero, is important in the operation of an alternating switch. The low dielectric strength of an ionized gas is to be attributed to the non-uniform potential gradient caused by the development of space charges. Calculations with certain approximations lead to the conclusion that in the case of arcs which are short in comparison with the diameter of their section, the first one or two hundred volts of dielectric strength are recovered almost instantly while later increments of dielectric strength are recovered at a rate lying between one million and one hundred million volts per second. Experiments have been carried out substantiating this conclusion.

For an arc which is long with respect to the diameter of its section the manner of recovery of its dielectric strength is not so simply stated. It is probably nearly correct to say that the ability to withstand a certain electric gradient is recovered almost instantly, and that later increments of dielectric strength return more slowly. The magnitude of this gradient varies in an inverse manner with the linear dimensions of the section of the arc as shown by experiments of Mason.

Experiments of Neher and others have shown the possibility of increasing the rate of recovery of dielectric strength by causing the arc to pass through holes in metal plates or the openings in metal gauze sheets.

A continuing chemical activity in the gases from an arc may cause the persistence of low dielectric strength for times long in comparison to those predicted by the preceding theories.

The success of the a-c. oil circuit breaker is to be attributed to all the factors considered in this paper.

15. Acknowledgment

This paper gives an account of general ideas and principles developed on the extinction of a-c. arcs by a considerable number of men working with the author for the past few years. Many of the topics touched upon are of great interest in themselves, and it is hoped that they will be elaborated upon in later papers by the men who have carried on the work. Besides the men already mentioned in the paper, those who have contributed largely to the topics discussed are B. P. Baker, R. C. Dickinson, G. H. Cole, and F. C. Todd, but first and foremost should be mentioned A. C. Crago, who in spite of his untimely death in 1925, continued to influence the work through the wealth of ideas and inspiration he left behind him.

Appendix

Mathematical Treatment of Extinction of an Arc Mobility of Positive Ions Considered

The arc space will be considered as consisting of two sharply defined regions, as in Fig. 4. One, next to the cathode contains only positive ions. The other, the rest of the gas space, contains positive and negative ions in equal numbers.

Let l = thickness of cathode region at time t.
i = current density at time t.
V = potential at point distant x from cathode at time t.

$$X = -\frac{\partial V}{\partial x}$$

v = velocity of positive ions toward cathode at point x.
k = mobility of positive ion.
e = electronic charge.
n = density of positive ions in cathode region at point x.
n_0 = density of positive ions in body of gas at time t.
n_{00} = initial density of positive ions.
α = coefficient of recombination of ions.
B = rate of increase of impressed voltage.
$V_0 = B\,t$ = potential impressed on electrodes.

In the cathode region we have the following relations:

$$i = n\,e\,v \tag{1}$$

$$v = k\,X = -k\frac{\partial V}{\partial x} \tag{2}$$

$$\frac{\partial^2 V}{\partial x^2} = -4\pi n e \tag{3}$$

the displacement current, $\frac{1}{4\pi}\frac{\partial X}{\partial t}$ being neglected.

Eliminating n and v from these equations and integrating,

$$\frac{\partial V}{\partial x} = \sqrt{-\frac{8\pi}{k} i\,x + A} \tag{4}$$

where A is a constant of integration. Substituting (4) in (3) we get

$$n = \frac{i/e}{k\sqrt{-\frac{8\pi i}{k}x + A}} \tag{5}$$

In the main body of the gas we have

$$\frac{d n_0}{d t} = -\alpha n_0^2 \tag{6}$$

Integrating this gives

$$\frac{1}{n_0} = \frac{1}{n_{00}} + \alpha t \tag{7}$$

If n_{00} is very large (7) becomes

$$n_0 = \frac{1}{\alpha t} \tag{8}$$

The neglecting of the displacement current in equation (**1**) is probably justified except near the boundary of the space charge region adjacent to the body of the gas. Here, we have space charge constantly being freshly exposed by the motion of the space charge boundary, and the conduction current is correspondingly reduced. In the main body of the gas, however, the displacement current is again zero, and the conduction current is the total current, and not very different from the conduction current in the space charge region away from the space charge region boundary. It seems then that the proper boundary conditions to use are the following:

$$n_0 = n(l) = \frac{i/e}{k\sqrt{-\frac{8\pi i}{k}l + A}} \tag{9}$$

$$\frac{d l}{d t} = \frac{i}{n_0 e} \tag{10}$$

Last, if the gradient in the body of the gas is negligible,

$$V_0 = V(l) \tag{11}$$

Applying (**11**) to (**4**) with the further boundary conditions that $V(0) = 0$ and using equation (**9**), the constant of integration A can be determined leading to

$$V_0 = \frac{k}{12\pi i}\left\{\left[\frac{8\pi i}{k}l + \left(\frac{i}{k e n_0}\right)^2\right]^{3/2} - \left[\frac{i}{k e n_0}\right]^3\right\} \tag{12}$$

(**12**) together with (**8**) and (**10**) and $V_0 = B\,t$ form a complete system of equations for determining l, n_0, and i. The solution is

$$l = \frac{\sqrt{B}}{\left[\frac{\alpha}{12\pi k^2 e}\left(\left[1+\frac{8\pi k e}{\alpha}\right]^{3/2} - 1\right)\right]^{1/2}}\,t$$

$$i = \frac{\sqrt{B}}{\left[\frac{\alpha^3}{12\pi k^2 e^3}\left(\left[1+\frac{8\pi k e}{\alpha}\right]^{3/2} - 1\right)\right]^{1/2}}\,\frac{1}{t}$$

$$V_0 = B\,t \tag{13}$$

The maximum gradient, $\frac{\partial V}{\partial x}$, which occurs at $x = 0$ is given by

$$\left(\frac{\partial V}{\partial x}\right)_0 = \left(\frac{12\pi e}{\alpha}\,\frac{1+\frac{8\pi k e}{\alpha}}{\left[1+\frac{8\pi k e}{\alpha}\right]^{3/2} - 1}\right)^{1/2}\sqrt{B} \tag{14}$$

If we assume as in sections 4, 5, and 6 that there is a definite critical breakdown gradient G for the gas, we have for the rate of recovery of dielectric strength,

$$B = \frac{\alpha^2}{144\,\pi^2 e^2}\left(\left[1 + \frac{8\,\pi\,k\,e}{\alpha}\right]^{1/2} - \left[1 + \frac{8\,\pi\,k\,e}{\alpha}\right]^{-1}\right) G^2 \quad (15)$$

Changing to practical units we have for B and G in volts per cm., and k in cm./sec. per volt/cm., and letting $e = 4.77 \times 10^{-10}$ e. s. u.

$$B = 1.02 \times 10^{13}\,\alpha^2\left(\left[1 + 3.59 \times 10^{-6}\frac{k}{\alpha}\right]^{1/2} - \left[1 + 3.59 \times 10^{-6}\frac{k}{\alpha}\right]^{-1}\right) G^2 \quad (16)$$

Substituting in numerical values we may take for air at normal pressure and temperature, $\alpha = 7.6 \times 10^{-6}$ (from section 5) $k = 1.4$[7], and $G = 30{,}000$. This gives $B = 3650 \times 10^6$ volts/second.

At 940 deg. (as in section 5) taking α as varying inversely as the cube, and G inversely as the first power of the temperature we have $\alpha = 1.06 \times 10^{-7}$, and $G = 7100$. As for k, according to Phillips,[8] and Kovarik,[9] the variation will be as the first power of the temperature and so at 940 deg., $k = 6.2$. With these values (**16**) gives $B = 81 \times 10^6$ volts per sec.

At 1200 deg. we have $\alpha = 4.8 \times 10^{-8}$, $G = 5600$, and $k = 7.5$ giving $B = 15.6 \times 10^6$ volts per sec.

Discussion

R. W. Sorensen: These figures given in Fig. 1, which are primarily theoretical figures, to show what happens across an arc, have been checked by us in the laboratory and we get figures of the same form.

Under oil the voltage across the arc is around 150 to 250 volts on an ordinary 200,000-volt breaker. The voltage across an arc in rather high vacuum is only of the order of about 12 to 13 volts, occasionally as high as 20 volts. The amount of energy to be accounted for can be measured by these voltages encountered and shows quite a difference, one being approximately ten times the other.

A phenomenon of interest shown by some oscillograms I have seen may make some other modifications of some of the work here. Under some conditions the current goes out before it crosses the zero line. In other words, you don't have to get down always to zero current apparently to have the arc go out.

That introduces another phase. If the long arc gradients could be eliminated by reducing all the arcs to short ones, this would not only tremendously simplify the theoretical problem, as Dr. Slepian has pointed out, but would also simplify actual operation. The work which he has suggested, which he and his associates are doing, in getting around these long arc gradients by means of holes through metals, et cetera, certainly will be of great value to us.

7. *Handbuch d. Physik*, Vol. XXII, page 323.
8. P. Phillip, *Proc. Roy. Soc.*, London A., Vol. 78, 1906, p. 167.
9. P. F. Kovarik, *Phys. Rev.*, Vol. 30, 1910, p. 415.

R. M. Spurck: Mr. Slepian's paper brings out a number of points as characteristics of the a-c. arc that have been recognized and studied by all circuit breaker designers for a number of years.

Two points impressed me. (1) The rate of voltage increase of the arc voltage after the voltage or current has passed through zero is one of the factors tending to cause a reestablishment of the arc. This rate of voltage reestablishment varies widely in different systems. (2) The tendency to reestablish the arc may be reduced by artificial means.

From an oil-circuit-breaker standpoint this means that if the tendency of the arc to reestablish is reduced a shorter arc length is obtained. This shortening of the arc length reduces the amount of gas formation in the breaker during its operation and the reduction in the amount of gas formation results in a reduction in duty on the breaker.

Consider first the rate of the rise of the reestablishment of the arc voltage. Inasmuch as it is dependent on the system and generator characteristics it is not, in general, usually practical to lighten the duty on the breaker by changing the system or generator characteristics. Neither is it possible from a practical standpoint to analyze a system and determine the rate of voltage reestablishment so that a breaker of light duty can be put on some systems and a heavier breaker put on systems having more severe duty.

It is, therefore, necessary to design an oil circuit breaker so that it will operate under the worst conditions of reestablishing voltage that any practical system can produce. The effect of reestablishing voltage also serves to explain why oil circuit breakers perform well in some locations and not so well in others.

Consider next the question of artificially reducing the effect of the reestablishing voltage on prolonging the arc. One of the artificial means suggested by Mr. Slepian was the use of shunt resistors across the circuit-breaker terminals. This he discards as impractical from a regular operation standpoint, and I quite agree with him.

Another way of artificially reducing the effect of the reestablishing voltage or the arc length under definite conditions of arc-voltage reestablishment is to increase the insulation strength of the arc stream by cooling or by pressure. In practise this has been done for a number of years by the use of the explosion chamber which utilizes the gas formation from the arc to increase the pressure around the arc stream and to blast cool oil through the arc stream. The efficacy of this device has been proved by many tests and wide experience.

C. D. Ainsworth: With the advent of high-potential alternating current came the oil circuit breaker. The principles of the earlier air-break circuit breaker designed for the older d-c. circuits crept into or influenced the design of this new device to such an extent that even today we are confronted with recommendations and demands for mechanical speed of break that involve us in designs that must expose to a high-power, high-voltage arc vast areas of oil. There must result, in addition to the destructive pressures during each succeeding cycle of arc, the excessive volumes of hydrocarbon gas which produce those pressures,—volumes of gas superheated, highly ionized but slowly deionizing, diffusing with relative slowness into the oil and thereby tending to prolong the cycles of arc which produce them. On the other hand, visualize an oil circuit breaker with an increased number—even a multitude—of shorter series arc gaps, each gap exposing a minimum of oil area and a maximum of electrode area and volume to the arc. Over the surface of the electrodes, by inter-reaction, the arcs are propelled to new and cooler zones. At the current zero, the arc zone is cooler, and the slowly de-ionizing hydrocarbon gases of the high-speed break arc to a large extent replaced by the more quickly de-ionizing metal vapor of the electrodes.

That such a breaker—one in which a much greater proportion of the thermal energy of the power arc is absorbed and converted

by the electrodes—approaches the desideratum of Dr. Slepian's paper is apparent. Initially it has the advantage derived from the condition of lower temperature as set forth in Dr. Slepian's equation (**13**) on page 4:

$$n = \frac{1}{\alpha t}$$

which equation is another way of stating that the number of ions, or the ionic density, varies directly as the cube of the absolute temperature. It follows, with the lower temperature and the correspondingly smaller number of ions, that the rate of recovery of the dielectric strength will be much more rapid, particularly where the more rapidly de-ionizing metal vapor is, as here, in greater proportion. Finally, the increased number of arc gaps, shorter in comparison to the electrode diameter, affects a condition of reduced space charges and consequent increase in rate f recovery of dielectric strength,—this is in addition to the 200-volt equivalent increments of dielectric strength instantaneously recovered at each gap.

Such an oil circuit breaker, however, is not a design of the future. Refined and perfected in the present, it is essentially a development of the past. The multi-break oil circuit breaker with energy-absorbing arcing contacts, under test and in the field has already demonstrated the fact that it does approach the desideratum of Dr. Slepian's paper.

J. B. MacNeill: The paper deals with means of opening circuits radically different from those now in use. Time will tell the degree to which these ideas can be incorporated in commercial apparatus. It may be said, however, that present methods in many cases are not considered altogether adequate, and there are individual switching problems where the application of the ideas dealt with in this paper seem entirely feasible. The oil circuit breaker has been developed far beyond the expectation of the original sponsors of the device and in general is giving adequate protection on all high-voltage or high-power a-c. systems. Any oil-immersed device, however, has the inherent disadvantage due to the oil content, and substitutes for oil immersed devices will always receive any consideration they may deserve.

F. W. Maxstadt: (communicated after adjournment) Dr. Slepian's contribution is of interest and great value in another field than the one pointed out in the paper.

Comparatively little has been known about the mechanism of the arc used in electric arc welding, either a-c. or d-c. It is now clear that the persistence of the a-c. welding arc which operates well below 165 r. m. s. volts cannot be due to residual ionization, but must on the other hand be caused by chemical activity which is known to be oxidation of iron vapor. The fact that the arc reestablishes itself in the same path after a current zero seems to me to prove that the chemical activity extends into practically every region of the arc volume. This easily accounts for the included impurities in the deposited metal.

The well known fact that arcs between iron electrodes in an atmosphere of hydrogen require voltages in excess of 165 r. m. s. shows that chemical activity in the arc stream is, under such conditions, too small to provide a mechanism for arc reestablishment.

This suggests a line of investigation to find a gas or mixture of gases which will provide chemical activity for restarting the arc at low voltage (for safety to the operator) and yet produce no harmful compounds in the deposited metal.

The same analysis applies to the d-c. arc which oscillograms show has unsteady characteristics, with current values approaching zero for an instant and suddenly building up to normal, aided of course by the reactive voltage of the series choke put into the circuit for the purpose.

Dr. Slepian's analysis of the time-phase relations between the arc current and voltage shows that successful arc-welding circuits must have sufficient series inductance, low series resistance, low condensance (capacity) between turns of the transformer or choke and high shunt resistance across the arc. Even the conducting vapors which surround the arc, but do not take part in the arc itself, are a cause of its extinction.

Civilization and the Engineer

President's Address

BY BANCROFT GHERARDI

What has the engineer contributed to civilization? Have his contributions been major factors in its development? It is important that we should know the answers to these questions, for sooner or later the standing of the engineer in the world in which we live depends upon these answers. To get them it is necessary to consider the development of civilization.

From the earliest days, mankind's primary need has been food. He cannot exist without it. In addition, in most climates he must have shelter, clothes, and fuel. As long as all human energy had to be devoted to meeting these needs, no margin remained for the improvement of man's condition, either physical, mental, or spiritual. It is to the extent that there is a margin of effort available after the minimum of these requirements is provided that civilization may develop. The existence and magnitude of such a margin has depended upon man's willingness and ability to produce beyond this minimum and the aids that he has in his work. The margin beyond that necessary for maintaining existence goes to the improvement of his status.

The students of the early stages of man's development measure the steps by which he has advanced by certain outstanding factors. Accepting the classification of Lewis H. Morgan, these are: the development of speech; the use of fire; the bow and arrow; the manufacture of pottery; the domestication of animals; the development of writing. In these, we find the beginning of civilization. And we find something more; something of the deepest significance to the engineer. Fire,—first used for warmth and cooking, and now our principal source of power. The bow and arrow—a machine by means of which man can apply his strength and dexterity more effectively. Pottery,—a manufactured article to minister to his household needs. Domestic animals,—a source of power under the control of man and a more reliable supply of food and clothing. Although at that time scientific knowledge was unknown, invention probably not recognized as such, and engineering not even dreamt of, in the bow and arrow and in pottery all were foreshadowed.

The struggle by man to learn the facts of nature and to utilize them has been slow and extended over ages. As we look back, at times progress has seemed to halt, and generally, there was no definite conception of what constituted progress or in what ways it should be sought, but nevertheless, the ground work was being laid and man was slowly moving forward.

There gradually grew up an appreciation that Nature was not whimsical or beyond understanding; that she has hidden treasures—materials and forces—that could be used by man if he would but learn what they were; that Nature was an inexhaustible treasurehouse if man would but find the "open sesame," the way to use her resources—and that the "open sesame" was to learn of Nature by studying her and not by trying to speculate what she should be; that we may theorize if our theories are based on facts and checked by experience, but that speculations without facts are idle dreams and that nothing that may be determined by observation may be safely accepted except as it is so determined. Early there were such minds,—Euclid, Archimedes, Aristarchus, Hipparchus,—but in their time they did not represent the common method of thought even of the educated people.

Then came a long period of halting, "the dark ages," during which not only did progress seem to cease, but in many cases it was discouraged by powerful authorities. But the greatest darkness always comes just before the dawn.

In the 16th and 17th centuries, the scene began to change rapidly. A number of wonderful men of whom I shall name only two, Galileo and Newton, devoted their lives to the study of nature, that is, to the getting of facts and to the effort to develop theories that would be consistent with these facts, and which could be used to postulate other facts which, if verified by observation, further extend knowledge. These men were the pioneers in our modern civilization. To these and to their successors in theory and application we owe the developments that constitute the determining factors of modern civilization.

And what are the characteristic features of the material aspects of modern civilization? They are power and machines.

Power by which man power and horsepower are multiplied to practically any extent that may be desired, and machines which, when driven by power, will make or do numberless things which man may desire. At last it is possible for man, aided by power and machinery, to produce so far beyond the primary needs of food, shelter, clothes, and fuel, that not only can he greatly improve the quantity and quality of these, but provide numberless other conveniences, comforts, and luxuries; and these results are attained today with shorter working hours than formerly were necessary to achieve a much lower standard of living.

These results have been a direct outcome of the work of the scientist, the inventor, and the engineer. And to these should be added other groups engaged in the practical application of science,—such as chemists, biologists, doctors, and architects. They have been

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contributed to also by the promoter, the manager, the banker, and the capitalist—all necessary factors in the development of modern civilization but without the products of science, invention, and engineering, they could not have builded as they have. For not only is our modern civilization based upon science and its applications but these have furnished the capital necessary to realize the results attained. For capital is the margin between what we produce and what we consume for our day-by-day needs, and this margin is mostly due to the applications of science. Suppose that today China should decide that it should have transportation and a communication system equivalent in proportion to its population to that of the United States. How would it go about getting such a system promptly? There is no way that it could do so. In material and labor, this system would cost say 200 billion dollars, for highways, railroads, motor cars, and telephone plants. This could not be borrowed, because aside from any question of credit, there is no such surplus available in the rest of the world; it is not to be had, because so much has not been saved in its whole existence of several thousand years.

This brief outline of the development in the material aspects of modern civilization indicates sufficiently the part that has been taken in it by the scientist, the inventor, and the engineer. I have confined myself largely to the material aspects because the very nature of engineering has to do with physical things. Should it be inferred that the engineer has made no contribution to the mental and spirtual advance of mankind? The facts by no means justify such a conclusion.

Consider the printing press and its relations to the diffusion of knowledge. The phonograph and what it has done for music. The moving picture, and now the talking movie and their part in education and entertainment. Radio broadcasting and its bringing millions in direct touch with the finest orchestras, the greatest educators and entertainers, and enabling millions to hear the President of the United States when he speaks on a public occasion. The farm telephone and the automobile and what they have done to break down the isolation of farm life. Is the world's great transportation system—railroads, motor cars, and steamships—used solely for business? Has travel ceased to have an educational value since the slowness, expense, and discomforts of the stage coach and of the sailing ship have been eliminated from it? And our communication system—mail, telephone, and telegraph—does it contribute nothing to our higher life? Is it never used except in relation to the material aspects of life?

If such contributions to our mental and spiritual development were all that have been given to the world by the engineer and his allies, they would be notable and more than refute the statement sometimes made that the engineer's contributions are solely materialistic. But this is by no means all.

The development of culture requires leisure from the struggle for existence. Was Athens the poorest nation in the world when it developed its wonderful literature and arts? It was materially the richest of its time. Was Florence, when it developed its school of painting, a poor and struggling city? Quite the reverse. Do we look today to Patagonia or Tasmania or to the Esquimos for high mental and spiritual development? We should if material welfare was inconsistent with spiritual and mental attainments. History justifies the statement that material, mental, and spiritual development as a whole go together, and that while a genius may develop under almost any conditions, a high and distributed culture is favored by a high and distributed material welfare. The scientist and engineer have sometimes done themselves injustice in assenting to statements and occasionally even suggesting, themselves, that they have not contributed except to the material welfare of the world.

Still another outgrowth of the development of science and of its application is the educational system of today. Not always is it realized that for the maintenance of our present educational system in this country, it is a necessity that there should be a sufficiently high standard of living to permit of the withdrawal from the immediate production of the necessities of life the hundreds of thousands of teachers who are directing this educational work and the millions of students who are taking part in it. It is also necessary that there should be available huge amounts of capital to be expended for the provision of buildings and other necessary equipment. All of these have been rendered possible only by the results of applied science in increasing the margin over and above that necessary for existence.

From the beginning of history, man has constantly struggled to improve his economic status. He has wanted an assured supply of food and more pleasing food, more comfortable and better lodging, more comfortable, better, and a greater variety of clothes, better shelter, more comforts of all kinds, more leisure and recreation, and now, through the tapping of the resources of nature, year by year and decade by decade, he is attaining these ends more and more, not only for the favored few but for the great mass of the people who, but a few decades ago, were believed to be condemned by the very nature of life in this world to an existence limited to the barest necessities. This sweeping change in the economic status of individuals and nations has given rise to many questions of a fundamental character. These questions have to do with social relations, education, economics, business, health, politics, and religion. They comprehend the whole relationship of man to man and of man to his environment.

These questions do not depend for their solution upon engineering principles which so largely rest upon the characteristics of physical and inanimate things, but they have to do rather with people and with human reactions. This, however, does not take them out of the field in which the engineer must be skilled to do his

work. For even though the engineer's main duty lies in the control of nature, the very organization of society which that control has given us means that the engineer, in his engineering work, must operate as a part of organized society and conduct his relations with others with due regard to human reactions. The conquest of nature on a large scale must be done by those who can use organizations of men. The modern engineer should have as great a capacity for human management, cooperation, and for dealing with others as the men in politics, religion, and other professions which are devoted primarily to the study of man. To the extent that the engineer can measure up to these requirements he may become a leader in other fields of action, as well as being a leader in his own.

Whatever may be the part of the engineer in the solution of these questions, his principal work and that which only he can do well, is to take the scientific facts made available by the scientist and, by their adaptation to practical ends, add to the welfare of mankind. And can we engineers, notwithstanding the stupendous advances of the 19th century and the gigantic steps forward of the first quarter of this century, doubt that still greater opportunities lie before us year by year, as with pride in the service that we render mankind and humility that so little has been done and so much remains to be done, we continue our work devoted to making this world a better and easier one to live in so that the burden of life may be lifted more and more from the shoulders of the average man.

The Diverter Pole Generator

BY E. D. SMITH[1]

Associate, A. I. E. E.

Synopsis.—This paper describes a new type of generator developed to overcome certain limitations inherent in the shunt and the compound generator, when used for charging batteries by the constant potential, the modified constant potential, and the floating methods.

THE advantages of the constant-potential, the modified constant-potential, and the floating method of battery charging are quite generally recognized. These systems require a source of direct current of constant voltage.

The following characteristics are desirable in a constant potential battery charging generator:

1. It should preferably have a flat voltage curve which does not rise with increasing current at any point, otherwise stability of the correct charging voltage cannot be maintained without manual adjustment.
2. It should operate safely as a motor without speed-up or polarity reversal during feed-back from the battery.
3. It should preferably have a slight rise of voltage with decreasing current near zero load as a means for curbing a tendency to swing over to discharge during light loads.
4. When floated on bus-control circuits, which are subject to heavy momentary loads, at some point above full load the voltage should abruptly droop to protect the generator from the high peaks by shifting them to the battery, otherwise the generator will be damaged.
5. After the occurrence of these peak loads the generator voltage should return to its original value.

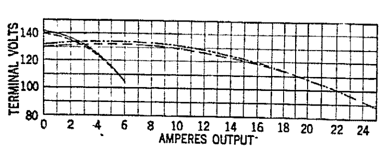

FIG. 1—VOLTAGE REGULATION CURVES OF 1½-KW. 130-VOLT SHUNT AND COMPOUND GENERATORS

———————— increasing load shunt generator
- - - - - - - - - - - decreasing load shunt generator
-.-.-.-.-.-.-. increasing load compound generator
-..-..-..-..-.. decreasing load compound generator

NOTE.—With shunt generator the voltage comes back slightly lower after an overload while the compound generators voltage comes back slightly higher after an overload

6. Commutation and efficiency should compare favorably with current standards.

The shunt generator is inadequate as its voltage falls too greatly with increasing load. Voltage regulators, when sufficiently sensitive, are necessarily delicate, and being susceptible to external conditions are difficult to keep properly adjusted.

The compound wound generator fulfils some of the conditions but has its limitations. In case of feed-back from the battery the generator will motorize and run at an excessive speed and thus may cause damage. This is due to reversed current in the series coils bucking the shunt winding and lowering the field strength.

Also, the voltage curve, Fig. 1, of a flat compound generator is too convex for constant potential battery charging. With this typical curve it is difficult to charge at any rate between zero and that corresponding

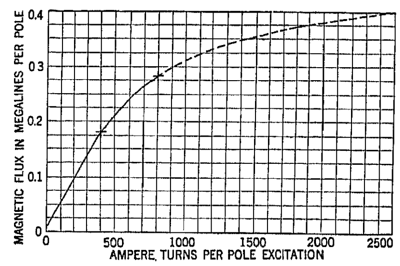

FIG. 2—MAGNETIZATION CURVE

———————— in producing the regulating flux in the diverter pole generator the magnetic changes are confined to the diverter pole and take place on this part of the curve
- - - - - - - - - - - in producing the regulating flux in the compound generator the magnetic changes occur in the main magnetic circuit and take place on this part of the curve

to the maximum voltage point, unless resistance is interposed between the generator and battery. In fact, any reduction of the charging current below the value corresponding to maximum voltage will usually be followed by a downward surge to discharge.

The voltage characteristic of the compound generator is curved, since the necessary magnetic changes produced by the series winding take place in the main magnetic circuit in accordance with the magnetization curve of the machine, (Fig. 2). Usually in obtaining satisfactory design it is necessary to work at least partly on the curved portion of the magnetization curve and the compound generator reflects this curvature in its voltage characteristic.

The following is a description of a generator designed for the specific purpose of meeting the exacting requirements necessary in a constant potential generator for battery charging:

In this generator, as shown in Fig. 4, a small diverter pole (1) spaced midway between the main poles, has a magnetic bridge connecting it to one of the main poles. Magnetic flux from the main pole will leak across this bridge to the diverter pole. A restricted section at 2

1. Rochester Elec. Products Corp., Rochester, N. Y.

Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.

in this bridge performs two functions: first, it limits the leakage, and second it serves as a magnetic choke, whereby it is possible to regulate the magnetism passing to the armature from the inner face of the diverter pole at 3. This regulation is possible since practically the whole of the main field ampere turns acting on the diverter pole are concentrated in overcoming the reluctance at this one restricted section, so that any reduction of the flux through this restricted section will release

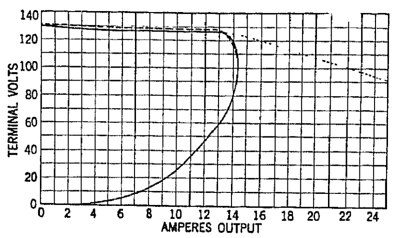

Fig. 3—Voltage Regulation Curves of 1½-Kw. 130-Volt Diverter-Pole Control-Bus Generator

———— increasing load self excited
- - - ▲ - - - decreasing load self excited
. . . . increasing load separately excited
Note.—The voltage comes back slightly higher after an overload

ampere turns expended here and raise the magnetic potential at 3 and consequently increase the magnetism passing to the armature at this point. At no load substantially all magnetic flux crossing the bridge will

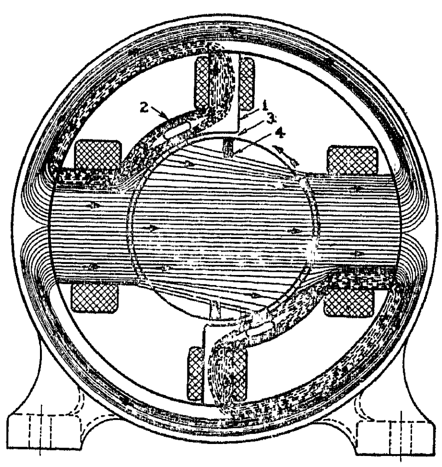

Fig. 4—Magnetic Flux Distribution at No Load

———— main flux
- - - - - - - - - - - leakage flux

take the low reluctance path through the diverter pole (1) back to the frame without pausing through the armature. A coil in series with the load circuit surrounds the diverter pole. This coil, as the load current increases, opposes and reduces the passage of magnetic flux through the diverter pole (1) to the frame.

The decrease of flux through the restricted section at 2, attending any reduction of flux through the diverter pole, (1), produces, as above stated, a rise in the magnetic potential at 3. The result is that part of the magnetic flux leaking across the bridge will take the air-gap path to the armature at 3 (Fig. 5), adding its value to the main pole flux and compensating for the voltage drop in the generator.

No variation of flux from the main pole to the armature occurs as there is no change in the magnetic potential at the main pole air gap. This follows, since neither the main pole nor the frame is highly saturated and the small variation of flux through these parts, due to the change of flux through the diverter pole, produces no appreciable variation in ampere turns of the main field excitation expended on this part of the main magnetic circuit.

A flat voltage curve is obtained since the magnetic changes produced by the series winding take place only in the diverter pole (1), and as the flux density here is kept low these changes occur on the low straight portion of the magnetization curve, thus eliminating most of

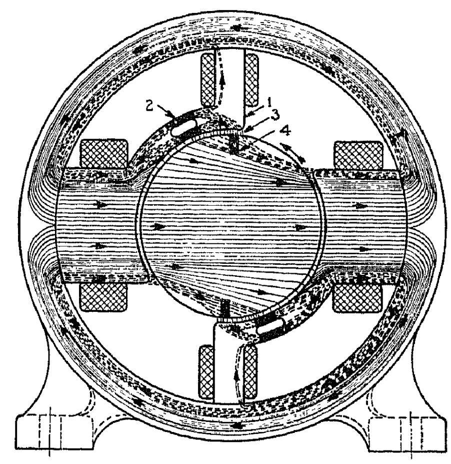

Fig. 5—Magnetic Flux Distribution at Full Load

———— main flux
- - - - - - - - - - - - leakage flux

the curvature from the generator voltage characteristic. These magnetic changes occurring in the diverter pole take place from a higher to a lower density on increasing the current output of the generator. This is the reverse of the occurrence in the compound generator, and the effect is to invert whatever part of the magnetization curve appears in the generator voltage characteristic, producing a concave instead of a convex voltage curve. By the proper adjustment of the diverter pole winding an almost straight curve is obtained with a slight rise on approaching zero load.

When motorizing, the main field strength is maintained substantially at its full value, as reversed current in the series coil can divert no further leakage due to saturation of the bridge restriction at (2). Also, any tendency for the diverter pole (1) to establish itself as an independent pole opposite in polarity to the main pole is limited to a safe value since the diverter pole already carrying the leakage flux quickly approaches saturation at any increase of flux through it, and safe operation as a motor is assured.

At some value of the load current the ampere turns

on the diverter pole equal those on the main pole and at this time the magnetic flux leaking across the bridge to the diverter pole is all re-diverted across air-gap 3, and there is no further leakage flux for an increased current to re-divert to the armature.

What occurs when the load is increased beyond this point is best illustrated by some recent tests.

The machine tested was a 1½-kw. generator, designed for floating with a 129-volt bus control battery. For the tests, this generator was equipped with a pair of movable exploring brushes by which the voltage around the commutator could be checked step by step and the flux distribution determined.

Fig. 6 shows the flux distribution when the generator

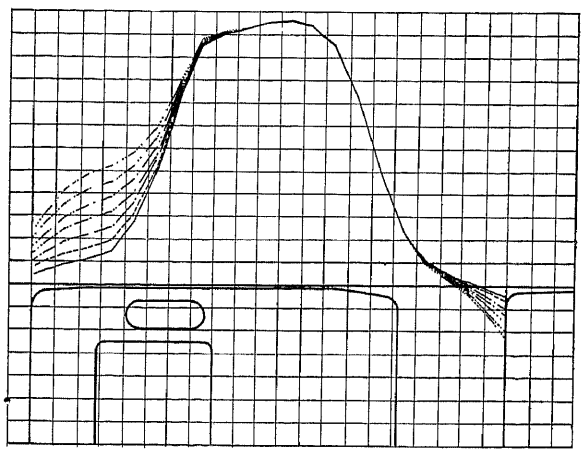

FIG. 6—FLUX DISTRIBUTION CURVES

When excitation of diverter poles is increased, armature carrying no current, brushes up, with main fields separately excited at constant value

——————— 0 amperes in diverter pole coils
- - - - - - - - - - 5 amperes in diverter pole coils
-.-.-.-.-. 10 amperes in diverter pole coils
-..-..-..- 15 amperes in diverter pole coils
-......... 20 amperes in diverter pole coils
——— .... ——— 25 amperes in diverter pole coils
——— ..... ——— 30 amperes in diverter pole coils

was operating with brushes up, shunt fields separately excited at a constant value and various currents passed through the diverter pole coils. This shows that the regulating flux is produced only at the diverter pole face, the flux from the main pole remaining practically constant.

Figs. 7 and 8 illustrate flux distribution under load, Fig. 7 showing flux changes up to the voltage cut-off point of 14 amperes. This shows the effect of armature reaction in the crowding of the main field to the right and in the partial suppression of the diverter pole field.

Fig. 8 shows that with any increase in the load current beyond the cut-off value of 14 amperes, instead of an increase in the diverter pole field there is a definite and decided collapse. With this collapse of the diverter pole field the terminal voltage falls and hence the main field excitation is reduced which accounts for the reduction of the main pole flux. The solid line of Fig. 3 shows the voltage regulation for this machine.

Fig. 9 represents flux distribution under conditions similar to those of Fig. 8 except that here the main fields were separately excited and maintained constant during the test. The broken line of Fig. 3 shows the voltage regulation for this machine.

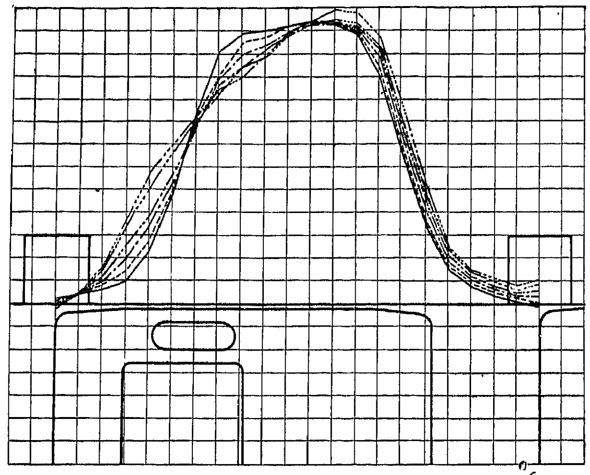

FIG. 7—FLUX DISTRIBUTION CURVES

When output is increased up to the voltage cutoff point at 14 amp. with main fields self excited

——————— 0 amperes generator output
- - - - - - - - - - 3 amperes generator output
-.-.-.-.-. 6 amperes generator output
-..-..-..- 9 amperes generator output
-...-...- 12 amperes generator output
-....-....- 14 amperes generator output

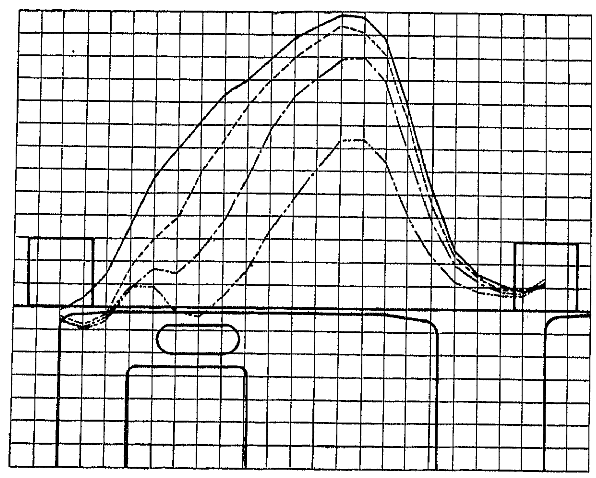

FIG. 8—FLUX DISTRIBUTION CURVES

When diverter pole generator is loaded beyond the voltage cutoff point at 14 amp. with main fields self-excited. Although the load was increased the amperes decreased due to the falling voltage

——————— 14 amperes generator output
- - - - - - - - - - 14.4 amperes generator output
-.-.-.-.-.- 14 amperes generator output
-..-..-.. 11.2 amperes generator output

This test also shows the collapse of the diverter pole field when the load current is increased beyond the 14-ampere point at which the ampere turns on the diverter poles equal those of the main pole.

It appears from these tests that when the ampere turns on the diverter pole exceed those on the main

pole, the flow of magnetism through the diverter bridge is reversed. Magnetism now flows from the diverter pole to the main pole and not from the main pole to the diverter pole. Under these changed conditions the magnetizing action of the armature assists the flow of magnetism through the bridge instead of

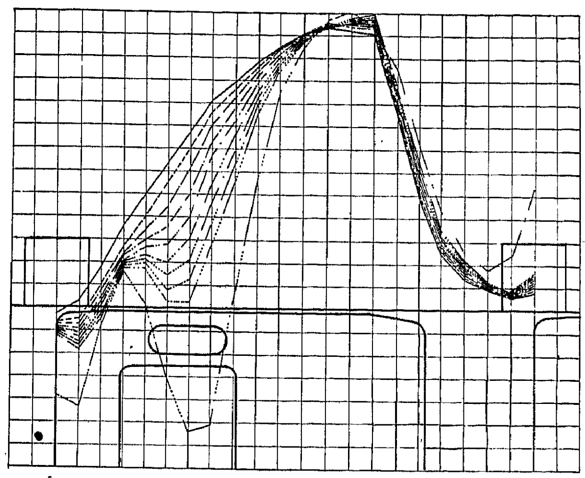

FIG. 9—FLUX DISTRIBUTION CURVES

When diverter pole generator output is increased beyond the voltage cutoff point at 14 amp. with main fields separately excited at constant value

————————	14 amperes generator output
- - - - - - - - -	16 amperes generator output
-.-.-.-.-	18 amperes generator output
-..-..-..-	20 amperes generator output
-...-...-	22 amperes generator output
-....-....-	24 amperes generator output
-.....-	26 amperes generator output
-......-	28 amperes generator output
-.......-	30 amperes generator output
-........-	45 amperes generator output

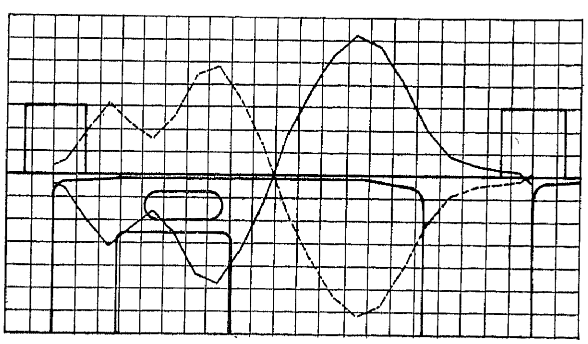

FIG. 10—FLUX DISTRIBUTION CURVES

During short circuit of diverter pole generator with main fields self-excited. The flux pulsates between the values shown by the solid and broken line curves

opposing it. In fact, under heavy loads the magnetism does actually reverse and pass from the armature to the bridge, and joining with the main pole flux, passes back to the armature at the hindward pole tip, constituting cross magnetism, while the magnetism from the diverter pole crossing the bridge flows backward through the main pole to the frame returning to the diverter pole without passing through the armature.

This theory requires the co-existence of two opposite magnetic fluxes in the main pole and also in the frame. However, it is the only apparent explanation of the definite collapse of the diverter pole field occurring with each increase of the diverter pole ampere turns above those of the main pole.

Fig. 10 shows flux conditions during short circuit, the flux pulsating between the values shown by the solid and broken line, the voltage and current pulsating also between the positive and negative values of 0.7 volts and 19 amperes.

Fig. 11, which represents conditions when generator is operated as a motor, shows some distortion of the main field due to armature reaction and a slight reduction of the diverter pole field due to reversed current

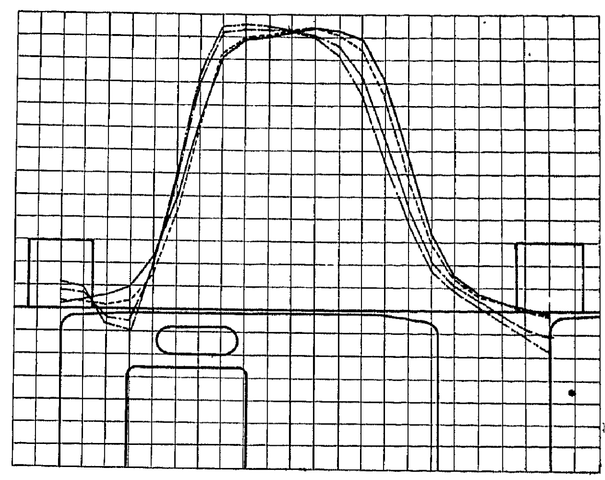

FIG. 11—FLUX DISTRIBUTION CURVES

When diverter pole generator is operating as a motor with varying load

————————	0 ampere output as generator
- - - - - - - - -	3 ampere input as motor
-.-.-.-.-	10 ampere input as motor
-..-..-..-	15 ampere input as motor

in diverter pole coils, this reduction being insufficient, however, to cause any instability in speed when motorizing.

When the load on the generator decreases a descending excitation is produced in the diverter pole coils and due to the effect of hysteresis this descending excitation leaves a slight residual magnetic field passing from the diverter pole face to the armature. This accounts for the voltage being slightly higher after an overload than before, as shown in Fig. 3.

Good commutation is assured as the diverter pole provides a commutating field of the correct direction for improving commutation and this field varies with the current output as in an interpole generator.

The efficiency will equal that of a similarly rated compound interpole generator since the excitation on the main poles will equal the shunt and series excitation and diverter pole excitation will be the same as that of the interpole of the compound generator.

Figs. 12 and 13 illustrate the pole and the complete field assembly of the diverter pole generator.

The characteristics of this generator are desirable for many battery charging applications.

In telephone exchanges when floated in parallel with the main battery, the generator maintains the voltage within the close limits required for correct operation of the equipment and furnishes the current directly to the exchange without its passing through the battery. Considerable economy is effected by the saving of power and in the increased life of the battery, and also by a saving of labor through the elimination of the necessity of manual voltage regulation.

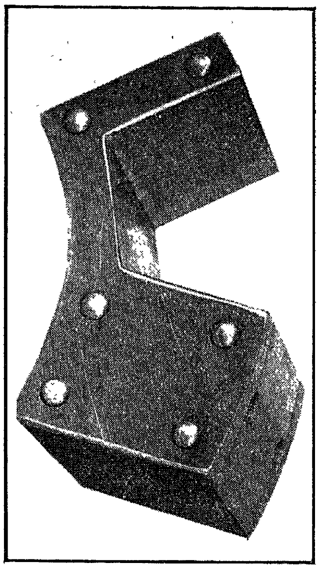

FIG. 12—DIVERTER POLE

The hole in the bridge does not appear as the two end laminations are punched without this hole the inner laminations have the hole as shown in Figs. 4 and 5

When several batteries are charged in parallel by the constant potential or modified constant potential method, as in recharging of vehicle and automobile batteries, the advantage of constant voltage, coupled with the ability to operate safely as a motor without polarity reversal or speed up during power failure is quite apparent.

In control bus operation, where a small generator is connected and operated continuously in parallel with a battery for switch operation, all of the desirable characteristics of this generator are utilized to advantage.

The flat voltage characteristic insures maintenance of correct floating voltage under varying load conditions with minimum supervision.

The ability to motorize safely without speed up or polarity reversal gives security during power interruptions.

The slight rise in voltage with decreasing current near zero load and the recovery momentarily to a slightly higher voltage after an overload combines to produce the desired stability of the correct floating voltage at the light load which constitutes the normal operating condition.

The sharp droop in the voltage just above full load amply protects both the generator and motor from danger of overload during switch operation.

The high voltage recovery after overload prevents the gradual diminishing of the generator voltage and consequent discharge of battery that occasionally happens with a shunt generator from the repeated overloading occurring in this service.

An advantage of the constant-voltage characteristic is that the battery is more quickly charged after it has been carrying load, since the battery is charged at a higher rate than with a generator of drooping voltage characteristic. This is an additional advantage as the higher charging rate tends to keep the battery, particularly the negative plates, in good condition. It also appears that the slight variations which may occur in the frequency of the power circuit should produce a beneficial effect in the battery when floated on a diverter pole generator. The voltage of the generator will follow these frequency variations and either slightly charge or discharge the battery as these variations are above or below normal. This will give a desired amount of activity to the negative plates without overcharging the positive plates.

It might appear that a generator with a drooping voltage characteristic is desirable for this floating method since the charging current is less affected by speed variations of the driving motor. However, as these generators are usually driven by induction motors their speed is not affected by variations in voltage, variations in frequency being the only cause of speed variation. Since the frequency of modern commercial power circuits is held within very close limits, no objectionable variation of motor speed is encountered which would justify the use of a drooping voltage generator for its damping qualities.

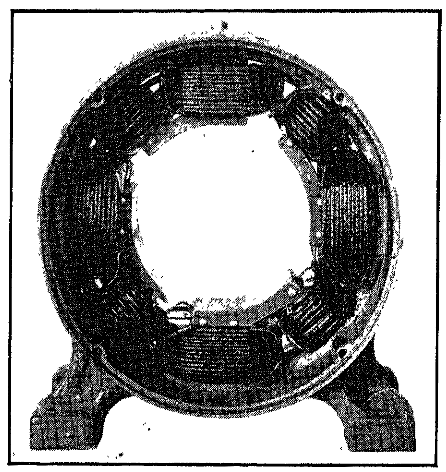

FIG. 13—DIVERTER POLE FIELD ASSEMBLY OF A $7\frac{1}{2}$-VOLT GENERATOR FOR CONSTANT POTENTIAL CHARGING OF AUTOMOBILE AND RADIO BATTERIES

The battery discharge during switch operation is not so great where the diverter pole generator is used, since the generator supplies the current demand up to its full load capacity, while the shunt generator gives little assistance to the battery at this time. This means that a higher bus voltage will be maintained during switch operation with the same size battery when floated with a diverter pole generator.

In some power applications, as for instance, car retarder operation, the load demands, while still intermittent, are more frequent and of longer duration so that the equivalent continuous load is a greater percentage of the battery capacity.

In this case it is desirable to restore the battery charge as much as possible between the heavy demands and it is also desirable that the bus voltage be maintained under varying load so that uniform response will be assured at the various control stations.

The generator designed for this application absorbs all loads up to 200 per cent of its normal rating, maintaining constant bus voltage up to this point and the battery is only called into action during loads in excess of this value.

Several thousand of these generators have been built and are operating on various battery charging applications, and their performance has justified the conclusion that the generator has many advantages where the constant potential, modified constant potential, or the floating method of charging is used.

The outstanding feature of this machine is its ability to give constant voltage with varying load and still be safe from speeding up or polarity reversal during feedback from the battery. However, the other characteristics, *viz.*, the inverting of the voltage curve which makes for stability of the charging voltage, the high voltage recovery after overload insuring voltage stability on light loads, and the drooping of the voltage on overload which protects it from serious overloading, contribute to its adaptability to the battery charging field.

An Amplifier to Adapt the Oscillograph
to Low-Current Investigations

BY SIGMUND K. WALDORF[1]

Associate, A. I. E. E.

Synopsis.—There has been need in several fields of electrical engineering research for a means to study time relations, wave forms, and similar phenomena where only infinitesimal currents are obtainable. The limitations and advantages of several possible methods of investigation are briefly compared, and the conclusion reached that the ordinary oscillograph can be most profitably adapted to such work.

The best form of vacuum tube amplifier for the work is then discussed, followed by a description of the steps taken in the design of a suitable resistance coupled amplifier. This amplifier is then described.

The results of tests showing quality of reproduction are given in the form of oscillograms and a characteristic curve. The recommended procedure to be followed and the necessary precautions to be observed in the use of the amplifier are given, with a short discussion of the abilities and possibilities of the oscillograph in its widened field of usefulness.

* * * * *

Introduction

THE ordinary type of oscillograph, operating on the D'Arsonval principle, has proved of great value in many fields, but the currents required to give workable deflections are so large as to restrict its use to cases where the available currents are greater than approximately a twentieth of an ampere. To obtain fairly large deflections, about a tenth of an ampere is necessary for alternating currents and almost a fifth for continuous currents. For low current investigations, where the currents are less than these values, one must look around for other means or apparatus to meet the requirements. The cathode ray oscillograph or the Einthoven string galvanometer might be mentioned, but they have several serious limitations for engineering problems for which the usual type of oscillograph has desirable characteristics. For combined sturdiness, ease of operation, transient recording, simultaneous multiple recording, and general utility the oscillograph far surpasses these other instruments.

Thus it has been thought worth while to adapt the oscillograph to small currents by means of a suitable vacuum tube amplifier. Such amplifiers are in common use for many purposes, so that their various forms and principles of operation are now widely known. The particular problem in this case was to obtain perfect reproduction over the entire frequency range of the oscillograph, a requirement calling for the careful selection of the proper circuit and careful subsequent design and construction. An amplifier circuit utilizing transformers cannot be expected to give perfectly equal amplification of all frequencies over a wide range. This can be predicted from theoretical considerations and has been shown experimentally in the unpublished effort of another investigator using a resistance coupled amplifier with a transformer in the output circuit. The purpose of this transformer was to obtain sufficient oscillograph current without requiring excessive plate current from the output vacuum tubes.

With this in mind, the resistance-capacity coupled and the straight resistance coupled amplifiers are the only ones that can be expected to give faithful amplification over a wide range of frequencies, so these were the only two seriously considered here. As will be seen later, the resistance coupled circuit was the only one found to be entirely satisfactory for all frequencies for which the oscillograph can be used, and it has the additional advantage that it amplifies continuous currents as well as alternating. The amplifier which has been built and is described in this paper will therefore meet all frequency conditions for which the oscillograph is applicable.

Preliminary Design and Tests

After it was decided to try the resistance-capacity coupled amplifier first, a survey was made to determine which of the many kinds of available vacuum tubes were best suited to the purpose. The Western Electric 102-D and 104-D tubes were thought to be the most desirable. Their nominal ratings as furnished by the manufacturer are given in the following table.

VACUUM TUBE RATINGS

	102–D	104–D
Normal filament current (amperes.)	0.95	0.97
Normal filament voltage	2 to 2.5	4 to 5
Normal filament voltage	2 to 2.5	4 to 5
Normal plate voltage	100 to 150	100 to 150
Normal grid voltage	0 to -3	-15 to -30
Normal plate current (milliamperes)	0.3 to 1.5	10 to 30
Plate-filament impedance (ohms)	40000 to 100000	1500 to 3000
Amplification constant	26 to 34	2 to 3
Maximum safe plate voltage	160	160

The plan for the amplifier was to place the input on the grid of a 102-D tube and have the plate circuit of

1. Graduate Student in Electrical Engineering, Johns Hopkins University, Baltimore, Md.

Initial and Best-Paper prize paper, presented at the Meeting of the Baltimore Section, District No. 2, Baltimore, Md., April 22, 1927.

this tube act on the grids of a number of 104-D tubes with their grids, filaments, and plates connected in parallel. The oscillograph element was to be connected directly into the combined plate circuit of these 104-D tubes. As no transformers were to be used anywhere in the circuit because of possible distortion, the 102-D tube was chosen for the first stage for its high amplification constant, and the 104-D tubes for the second stage for their high current output at relatively low

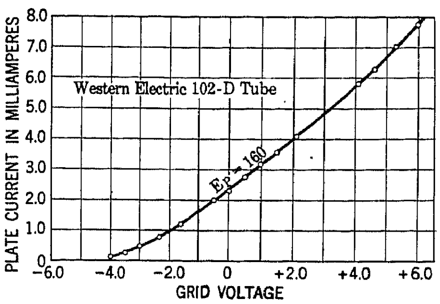

Fig. 1—Typical Characteristic of a Western Electric 102-D Vacuum Tube with Negligible External Plate Impedance. Plate Voltage = 160

plate voltage. As it could be seen that the plate current requirements of the output tubes would be severe, the parallel arrangement in the output stage was called for. The power requirements of both these types of tubes are not exceptional and can be handled easily.

The characteristics of the two types of tubes were taken with the plate milliammeter the only external plate impedance, holding the applied plate voltage constant at the maximum safe value (160 volts). These characteristics are given in Figs. 1 and 2. The

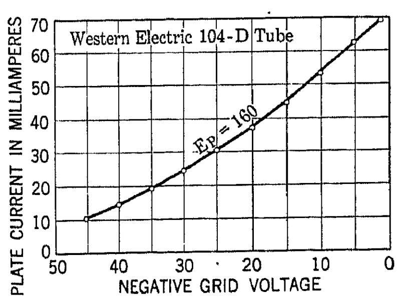

Fig. 2—Typical Characteristic of a Western Electric 104-D Vacuum Tube with Negligible External Plate Impedance. Plate Voltage = 160

characteristic curves of the 102-D tube were then taken with appreciable external plate impedance to determine the proper resistance to give a perfectly straight characteristic. After a few trials, a plate impedance of approximately 25,000 ohms was found to be the proper value, giving a straight characteristic for negative grid potentials between zero and approximately three and a quarter volts. Under these conditions the voltage variation across the plate impedance was slightly more than 28 volts, as calculated from the plate impedance and the change in plate current.

The characteristics of the 104-D tubes indicated that these tubes would give straight line reproduction in use if the total grid voltage variation did not exceed a maximum value of 30 volts, varying from − 3 to − 33 volts.

A resistance-capacity coupled amplifier was then made up using the connections of Fig. 3. This was in two stages—the first designed for voltage amplification with the 102-D tube, and the second for maximum possible current output with two 104-D tubes in parallel. The bias on the first stage was − 1½ volts and that on the second was varied from − 15 to − 22½ to determine the most suitable value. The plate impedance of the first tube was two lavite resistance units in series, of 25,300 ohms total resistance. The two-microfarad coupling condenser was an ordinary tele-

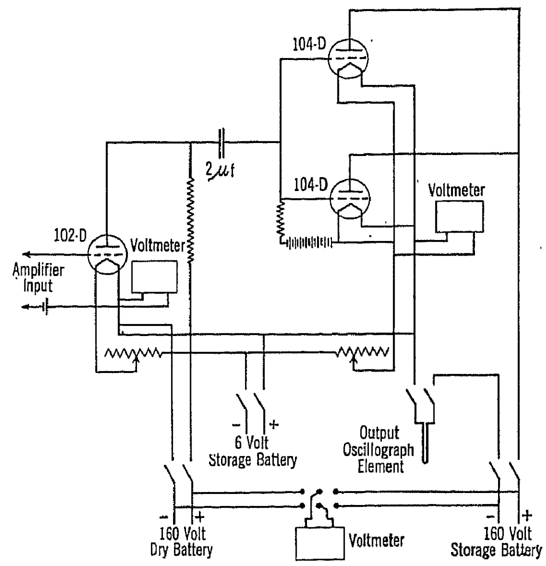

Fig. 3—Connections of the Trial Resistance-Capacity Coupled Amplifier

phone condenser of waxed paper and tinfoil. The grid leak was ordinarily 100,000 ohms of lavite resistors, but was varied from about 140,000 to about 40,000 ohms to find the best value. Other necessary information is given in the diagram of Fig. 3.

To test the quality of reproduction of the amplifier, it is necessary that the input wave form be recorded as well as that of the output, and that the input as indicated by the input oscillograph element be absolutely the same as that impressed on the amplifier input. To attain this, the input connection shown in Fig. 4 was used for all tests of reproduction. The 57- and the 355-ohm resistances were tube rheostats used as a potential divider to give the desired voltage across the 4-dial resistance boxes. This voltage was read on a General Electric Type P3 voltmeter with a 30 volt range. The resistance R_G was zero in the earlier tests but had values up to 105,000 ohms in the tests of reproduction of the final amplifier. Its function in the input grid circuit will be explained later.

In order that all the conditions of testing should be known in the earlier work, a sine wave was used for the input. The potential divider was adjusted to give exactly 21.2 volts on the 30-volt voltmeter, which gave a peak value of 30 volts across the 4-dial resistance boxes. This gave a total voltage variation across these boxes of 60 volts between opposite alternating wave peaks. For example, in the first test it was desired to have an input grid variation of exactly three volts. Using 20 ohms per volt based on peak values, R_1 was dialed to 30 ohms and R_2 to 569 ohms. This value of R_2 allows

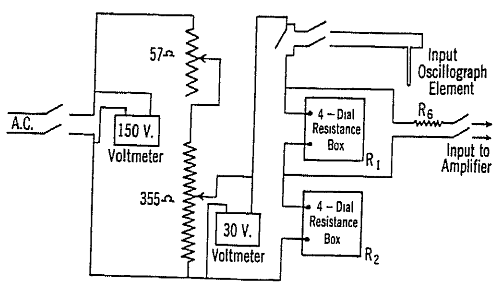

FIG. 4—CONNECTION USED TO IMPRESS KNOWN INPUT ON THE AMPLIFIER

one ohm for the resistance of the input oscillograph element, which was actually 1.5 ohms. In this manner, the input conditions were known very exactly to be the desired three volts variation.

The amplifier of Fig. 3 was tested in this way and showed poor reproduction. The amplitude of the output wave was only half an inch between opposite peaks,

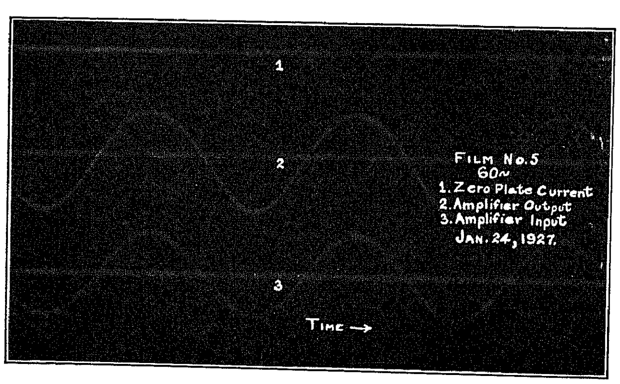

FIG. 5—DISTORTION OF A 60-CYCLE SINE WAVE BY THE OUTPUT STAGE OF THE TRIAL RESISTANCE-CAPACITY COUPLED AMPLIFIER

and showed a decided flattening effect on waves of one side and a peaking effect on those of the opposite side.

To determine which stage of the amplifier was responsible for the distortion, the first stage was removed and 30 volts grid variation placed directly on the 104–D tubes through their coupling condenser and grid leak. To increase their plate output, a third tube was added in parallel to the other two, and the three operated under these conditions gave an amplitude of approximately an inch. The distortion was still decidedly present, as can be seen in Fig. 5. The straight line marked "1" on this oscillogram was obtained when the output oscillograph element was disconnected from the output plate circuit and no current flowed through it.

Further similar trials were made with this form of amplifier, investigating the effects of various values of coupling condensers, grid leaks, grid bias, and variations of grid input potential. But even at relatively small amplitudes the distortion was very apparent, if not at one frequency, at another. Finally the decision was reached that it was quite hopeless to attain perfect reproduction over the desired range of frequencies using resistance-capacity coupling.

FINAL FORM OF THE AMPLIFIER

Utilizing the experience obtained in the experiments on the resistance-capacity coupling, and with the aid of a few further experiments, a plain resistance coupled amplifier was finally designed and built according to the plan of Fig. 6. As there are several

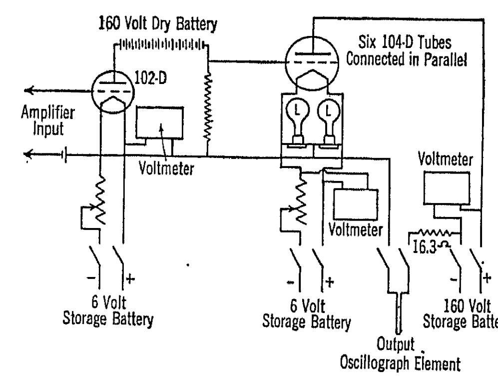

FIG. 6—FINAL FORM OF THE PURE RESISTANCE COUPLED AMPLIFIER

interesting features included in this amplifier, it will be described in some detail.

It is necessary that each stage have its own set of filament and plate batteries. The battery requirements of the first stage are not unusual. The filament voltage of the 102–D tube is kept at 2.25 volts and draws about 0.9 ampere filament current. A 6-volt filament storage battery is used simply for convenience, as the usual commercial storage battery has three cells. Naturally, a 4-volt battery would be just as satisfactory for the purpose. The plate battery for this stage is seven blocks of the usual 22½-volt radio B batteries. Using fresh batteries, the plate voltage is very close to 160 volts. These batteries should maintain this voltage for considerable time as the current drain is only a little over a milliampere.

The battery requirements are much more severe in the second or output stage. The current drain on the 6-volt filament storage battery is 6.25 amperes when the filament voltage is held at the fixed operating value of 4.5 volts. The filament rheostat is two 15-in. lengths of No. 18 advance wire, suspended together in

parallel between two porcelain insulator knobs. The slider is a 15-ampere battery clip with a lead from the negative battery terminal. One end of the resistance wires is connected to the common negative filament lead.

The plate battery is a heavy-duty radio storage battery with a current rating of a quarter of an ampere. This battery has a number of end cells so that the voltage can be maintained at 160 volts. When the amplifier is in operation, the terminal voltage of this battery falls off two or three volts due to the internal resistance of the cells. When the additional plate impedance was placed in series with the output oscillograph element, this was kept in mind. If the storage battery were of sufficient capacity to maintain constant voltage, this extra resistance would be made greater than 16.3 ohms. Because of this slight voltage variation, it has been found desirable to have the plate voltmeter connected across this battery all the time it is in operation, so that the plate voltage may be noted at any time.

The added plate resistor of 16.3 ohms was found necessary to help straighten the characteristics of the 104–D tubes. As it must carry as much as a quarter ampere it is made of No. 24 double cotton-covered advance wire wound non-inductively on a wooden spool. A further aid in straightening the characteristic is the potential divider arrangement of the two incandescent lamps *LL* in series across the tube filaments. When under operating conditions the maximum plate current is drawn from each tube, the plate current is of the order of seven per cent of the normal filament current. If all this flows into the filament at one end there will be excessive heating of the filament at this end. There will then exist an appreciable change of the filament temperature with change in plate current, causing an irregular amplifier characteristic. Providing two parallel paths for the plate current reduces this effect to a minimum by giving a more even division of the current between the two ends of the filament.

Using a potential divider of two 200-watt, 120-volt, Mazda C lamps as shown, actually improved the operation of the amplifier considerably. Of course, besides having the effect described, these lamps are additional resistance in the output circuit, thus serving a double purpose. The lamp resistance varies with the applied voltage, but with the constant filament voltage maintained, their combined series resistance was found to be fixed at about 15 ohms.

The negative grid bias on the 102–D tube is 1.6 volts furnished by a single small flashlight cell. No bias battery is needed on the 104–D tubes; the proper bias is furnished by the drop across the plate impedance of the 102–D tube. The voltage drop across this plate impedance ranges from 4.9 to 33.1 volts in the working interval. This impedance is 24,500 ohms pure resistance of two lavite cylinders in series.

To reduce to a minimum inductive and capacity effects which are troublesome at the higher frequencies, the amplifier has been made as compact as possible. The amplifier itself, with its tubes, lamps, resistances, and miniature filament voltmeters, is all mounted on a board 25 by 12 in. The dry B batteries, the two filament and the input switches, and the plate voltmeter (of the regular larger size) are on the table supporting the amplifier board. The total table space used is 29 by 34 in., which allows space to spare. The two filament storage batteries and the plate storage battery are placed on the floor beneath the table. Provision has also been made to charge the filament storage batteries easily by the use of double-pole, double-throw switches in place of the single-throw filament switches of Fig. 6. To avoid unimportant complications, these connections have not been shown on the amplifier diagram. Otherwise, the amplifier is as simple as the diagram indicates.

Tests of Reproduction

The performance of an amplifier under all possible conditions must be, necessarily, the criterion of its worth. This particular amplifier has been tested under a number of differing conditions and has been found to have excellent properties.

As the amplifier is to work with the oscillograph, all tests were made considering the combination as a single unit designed to record low-current phenomena. The conditions on the oscillograph as well as those on the amplifier were kept under close observation. For all tests, the tensions on the oscillograph elements were kept at five ounces, and when observations were made, the galvanometer field current was kept at the rated saturation value of 0.35 ampere or slightly above.

Resistance coupling is a d-c. amplifier circuit and permits of taking a static characteristic curve. This was done, (for results see Fig. 7) where the sensitivity of the output oscillograph element was 40 milliamperes per centimeter deflection. As can be seen, straight line reproduction is obtained for grid potentials between zero and -3.2 volts, with a total change of oscillograph deflection of 5.2 centimeters. With a grid bias of -1.6 volts on the input, operation takes place in the middle of this range. In tests where the input wave form is unknown, the amplitude is kept well within these limits, so that any peaks present will not be distorted by being beyond the straight portion of the curve.

The static characteristic curve brings out an interesting property of this amplifier, which is that the amplifier cannot be seriously overloaded. This is due to cut-off occurring in either the first or second stages when the input grid potentials become excessive. The phase of the input is reversed in the output, that is, an increase of input grid potential decreases the output current. If the input grid is given an increase in potential, the plate current of the 102–D tube increases with a con-

sequent decrease in the potential of the 104-D tube grids. This decreases the output current. If the input voltage is too high, the output grids become sufficiently negative to cause close to cut-off in the 104-D tubes. If the opposite condition should occur, the input grid becoming strongly negative, the plate current of the

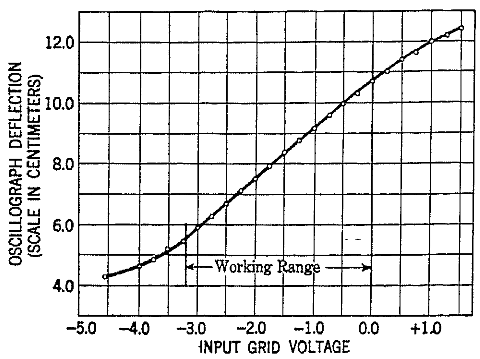

FIG. 7—CHARACTERISTIC OF THE COMBINED VACUUM TUBE AMPLIFIER AND OSCILLOGRAPH

102-D tube will be very small and the output grids will approach zero potential, which they cannot exceed. This limits the output current to that which the 104-D tubes furnish with zero grid potential. Although this may damage the oscillograph element if left on for any time, the amplifier should not be affected.

Tests were made with alternating currents over a wide range of conditions. It is here that the resistance R_G in the input grid circuit serves an important purpose.

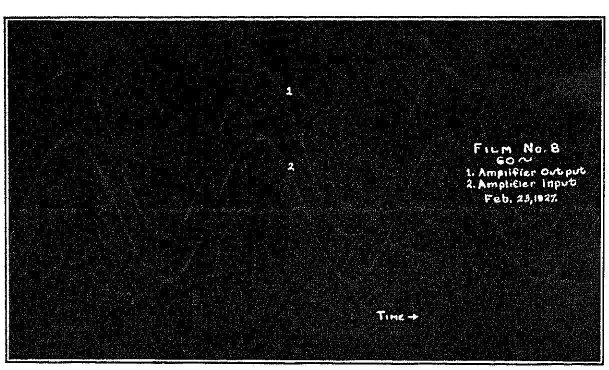

FIG. 8—REPRODUCTION OF A 60-CYCLE SINE WAVE

(See Fig. 4) This was given values from zero to 105,000 ohms. If the grid currents were of the same order of magnitude, or even somewhat smaller than the currents to be amplified, there would be distortion introduced when the grid circuit impedance is made very high. The effect of this grid impedance is not noticeable for any values within these limits. The oscillograms shown are with this high resistance inserted. This amount was used because the author was most interested in the behavior of the amplifier when the currents to be amplified are of the order of five to ten microamperes, or larger. With these small currents the necessary cuit resistance to be inserted to obtain proper input grid potential variations is of about the stated value. If it is desired to amplify smaller currents than this, or the available voltage variation is too low to give good oscillograph amplitude, a third stage may be placed on the amplifier, identical with the 102-D stage and acting on this stage with the necessary change of grid bias. Under such conditions the input voltage variation need be only little more than a third of a volt and the amplifier currents possibly of the order of a microampere for maximum amplitudes.

Figs. 8 and 9 show the quality of reproduction of the

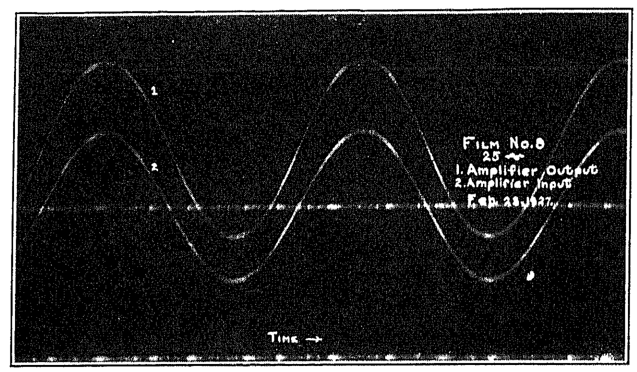

FIG. 9—REPRODUCTION OF A 25-CYCLE SINE WAVE

amplifier with a sine wave impressed. The straight lines on these figures are the zero lines of the input voltages; no zero lines were taken on the output. The amplitudes of the output waves are two inches, which is about the limit for perfect reproduction. It should be borne in mind that the relative amplitudes of the input and output waves have no significance, as the size of the input wave depends on the ohms per volt in the four-dial resistance boxes of the input connection, whereas the output wave depends upon the input grid voltage variation.

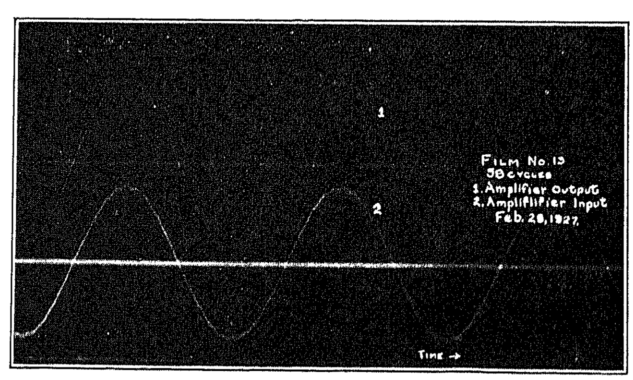

FIG. 10—REPRODUCTION OF A 58-CYCLE ALTERNATING WAVE OF IRREGULAR FORM

Fig. 10 shows the reproduction of an a-c. wave with slot ripples present on the peaks; Fig. 11, a fairly smooth wave taken at a higher frequency, where the wave forms of the cycles varied. The amplitude on Fig. 10

is $1\frac{3}{4}$ in. between opposite peaks; that on Fig. 11 is $1\frac{1}{2}$ in.

Fig. 12 is of special interest as this is a record of a transient phenomenon of very irregular wave form. As the form of the wave was unknown, when the record was being made, the amplitude of the light spread of the oscillograph was widened until it was about $1\frac{1}{2}$ in., by increase of the resistance across which the input was connected. This allowed ample room on the straight portion of the amplifier characteristic for any peaks that might have been present and not apparent on the

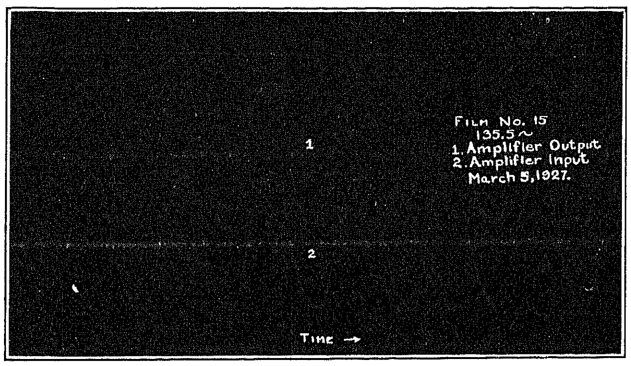

Fig. 11—Reproduction of a 135.5-Cycle Alternating Wave of Varying Form

stationary ground glass scale. Then the film was exposed and the record obtained. The arrow points to a short oscillation which occurred and which was reproduced very well. As this oscillation is at about 4500 cycles and is amplified satisfactorily, it is indicated that the amplifier will take care of all conditions which the oscillograph itself can handle properly at the higher frequencies.

A careful study of these tests shows that the amplifier

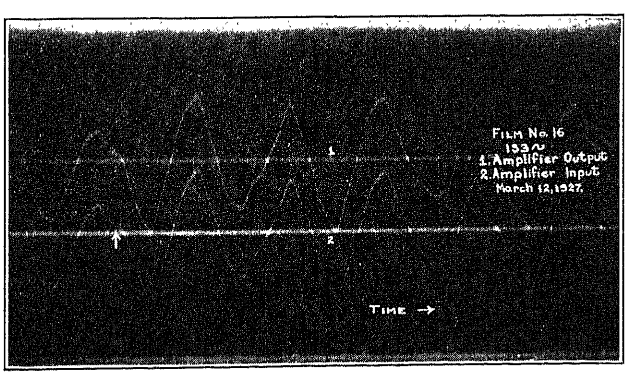

Fig. 12—Reproduction of a very Irregular Transient Alternating Current

The arrow indicates the presence of a damped oscillation of approximately 4500 cycles per sec.

described gives identical reproductions and that it is competent to extend the range of the oscillograph down to five or ten effective microamperes at one effective volt on alternating current, or slightly higher voltage on direct current.

Procedure and Precautions

A few words should be said concerning the actual use of the amplifier. It is believed that it has been reduced to its simplest possible form and that apparatus requiring the operator's attention is at a minimum. The observations and tests described have been made by a single operator without difficulty. The ordinary care exercised in the use of the oscillograph and of

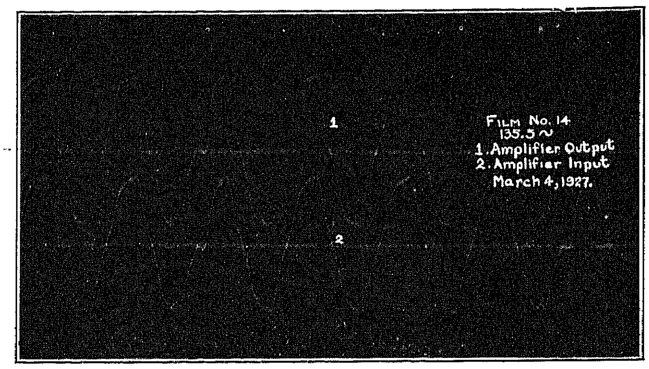

Fig. 13—Accentuation of Higher Harmonics by the Amplifier due to Unduly Long Plate Battery Leads

vacuum tubes should be sufficient for the proper operation of the combined amplifier and oscillograph.

Whenever the amplifier is used, the input grid battery and the dry cell plate battery should be tested to see that their voltages are correct. The grid battery, especially, should be watched and not allowed to get below approximately 1.54 volts. If the maximum amplifier output is to be obtained at all times, it

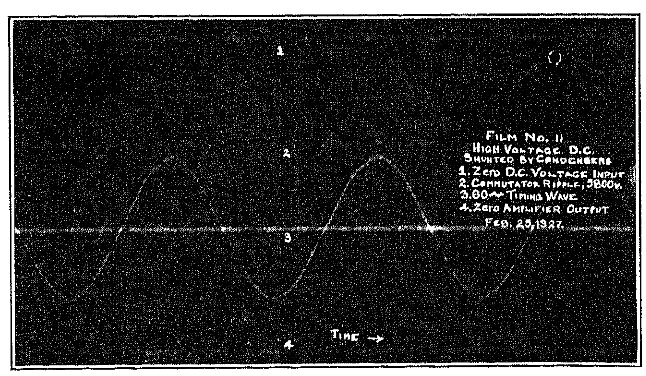

Fig. 14—An Application of the Amplifying Oscillograph to a High-Voltage D-c. Investigation

has been found advisable to hold this grid bias close to 1.60 volts.

The filament and plate storage battery voltages should be kept as close to the proper values as convenient. Slight changes in these have not been found to cause distortion if such changes do not occur during the interval when the film is being exposed.

As mentioned previously, if a storage battery is available for the plate supply of the 104-D tubes which has sufficient capacity to maintain its voltage, the value

of the additional resistance in the output circuit must be made greater than 16.3 ohms by about 8 ohms. Of course the exact value must be determined by experiment in any particular instance.

To lengthen tube and oscillograph element life, the output circuit should be closed only so long as is necessary for proper adjustments and observations. It is advisable also to turn off the filaments of the vacuum tubes as soon as convenient.

An interesting effect of unduly long leads is illustrated in Fig. 13. When not in use on the amplifier, it was desired to use the plate storage battery for other work, so about 150 ft. of insulated twisted pair were run from the battery to the other apparatus in question. Shortly after this had been done, the test of reproduction was made which is shown in Fig. 13. The irregularities of the input are much exaggerated in the output, indicating over-amplification of the higher frequencies. This new development in the amplifier was puzzling until the presence of the additional long leads came to mind. They were removed and the reproduction returned to its former good quality. The explanation of this effect is that the long twisted leads acted as a by-pass condenser across the plate battery for the higher frequencies.

An instance of the usefulness of the amplifier is given in Fig. 14, which is a test made to observe the commutator ripple of a high-voltage d-c. generator when shunted by condensers. Some research was in progress for which it was desirable to determine what could be done to remove the ripple of a 15,000-volt machine. The oscillograph was the logical means to employ for observation of the ripple, but as the oscillograph ordinarily requires about a tenth of an ampere for such indications, it is difficult to obtain and handle resistance for this current and voltage to be placed in series with the oscillograph element. So a suitable resistance, taking about three milliamperes at the given voltage, was connected across the generator and the amplifier input connected to a four-dial resistance box in the tail circuit. For this work a negative input grid bias of about three volts was used and the input so connected as to make the input potential more positive for increased applied voltages. The distance between "1" and "2" on Fig. 14 represents 5800 volts. Thus the oscillographic study was made very easily at a number of different voltages with the amplifier, which would have been very troublesome otherwise.

Conclusion

It was the purpose of this work to develop a simple and convenient method for making oscillographic studies of high-voltage and low-current waves and similar phenomena—one which could be depended upon to give perfect reproduction of very small currents, preserving them in their true phase relations as well as in form. It is felt that this has been accomplished and that the amplifying oscillograph, if the combined amplifier and oscillograph may be so called, should prove a useful instrument in electrical engineering research. The oscillograph, already valuable in a wide field, has now had its range extended down to currents of about ten microamperes or less.

Acknowledgment

The author wishes to acknowledge his indebtedness to the Department of Electrical Engineering of the Johns Hopkins University for the use of its apparatus and laboratory where this development has been accomplished. He also wishes to express his appreciation to those at the University who have shown interest in the progress of the work and who have made suggestions from time to time.

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